Chimera baryon spectrum in the Sp(4) gauge theory

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The collaboration

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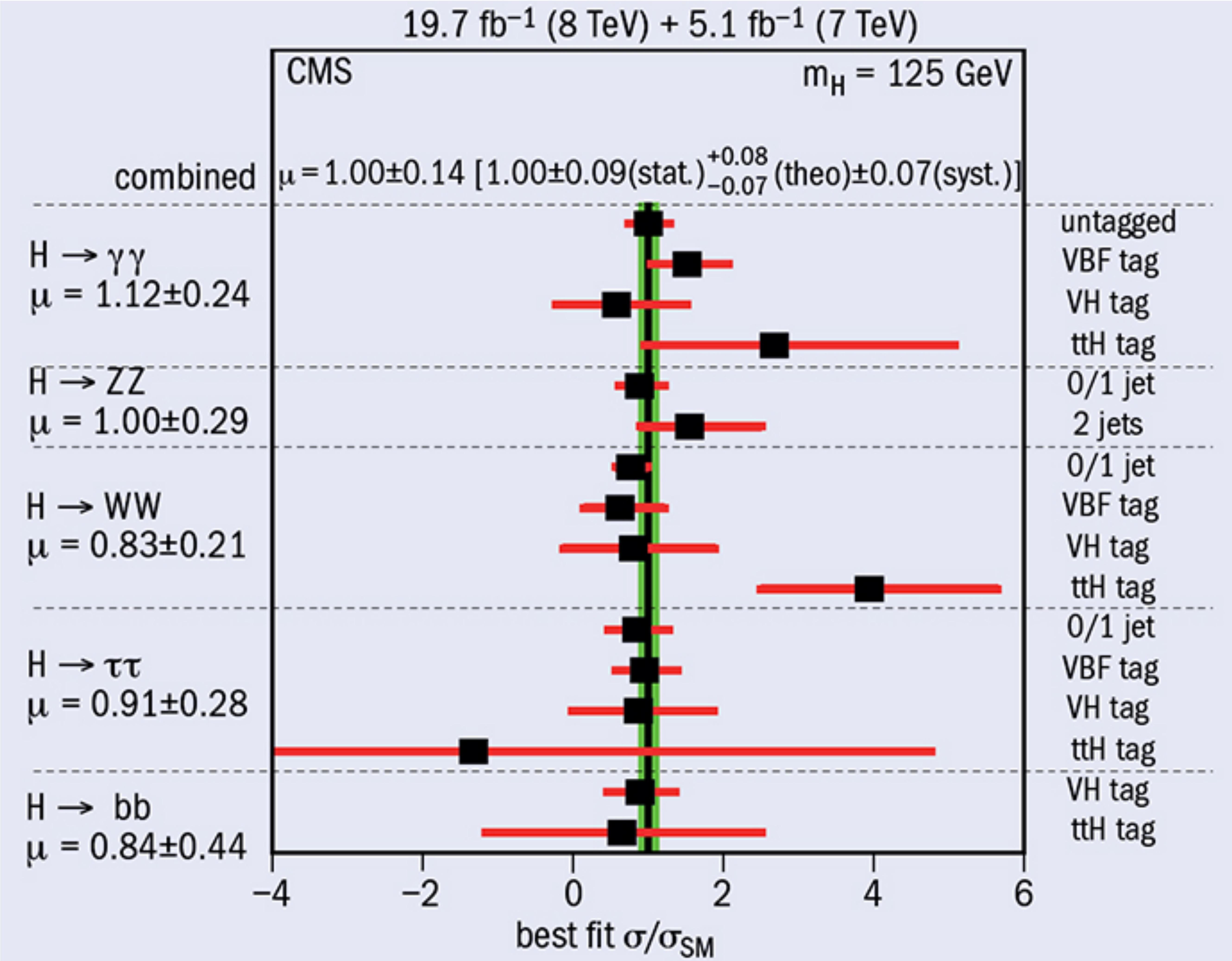
Outline

- Motivation: why composite Higgs?
- Lattice studies: our works and the chimera baryon
- Conclusion and outlook

Why composite Higgs?

Further understanding of the Higgs boson…



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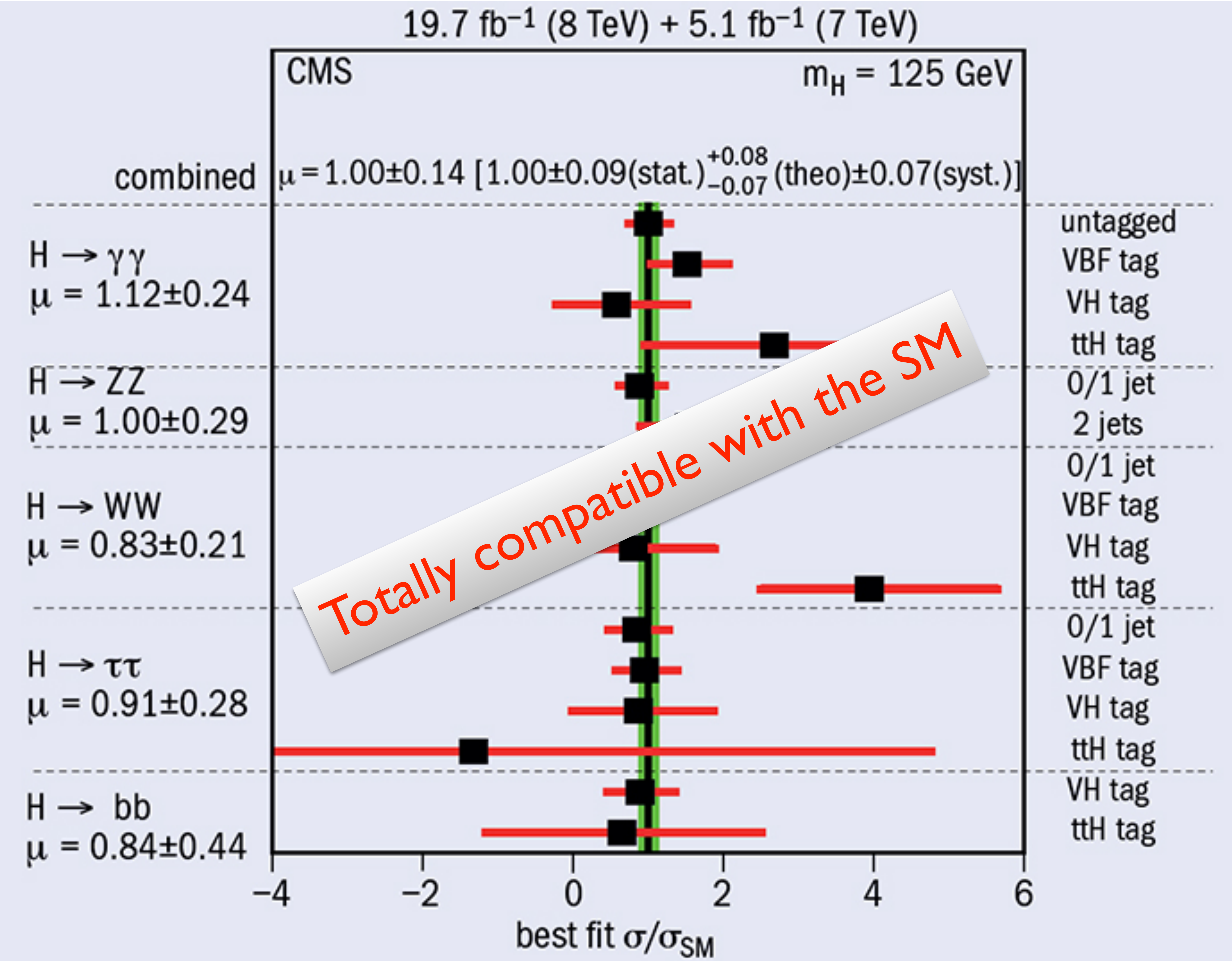

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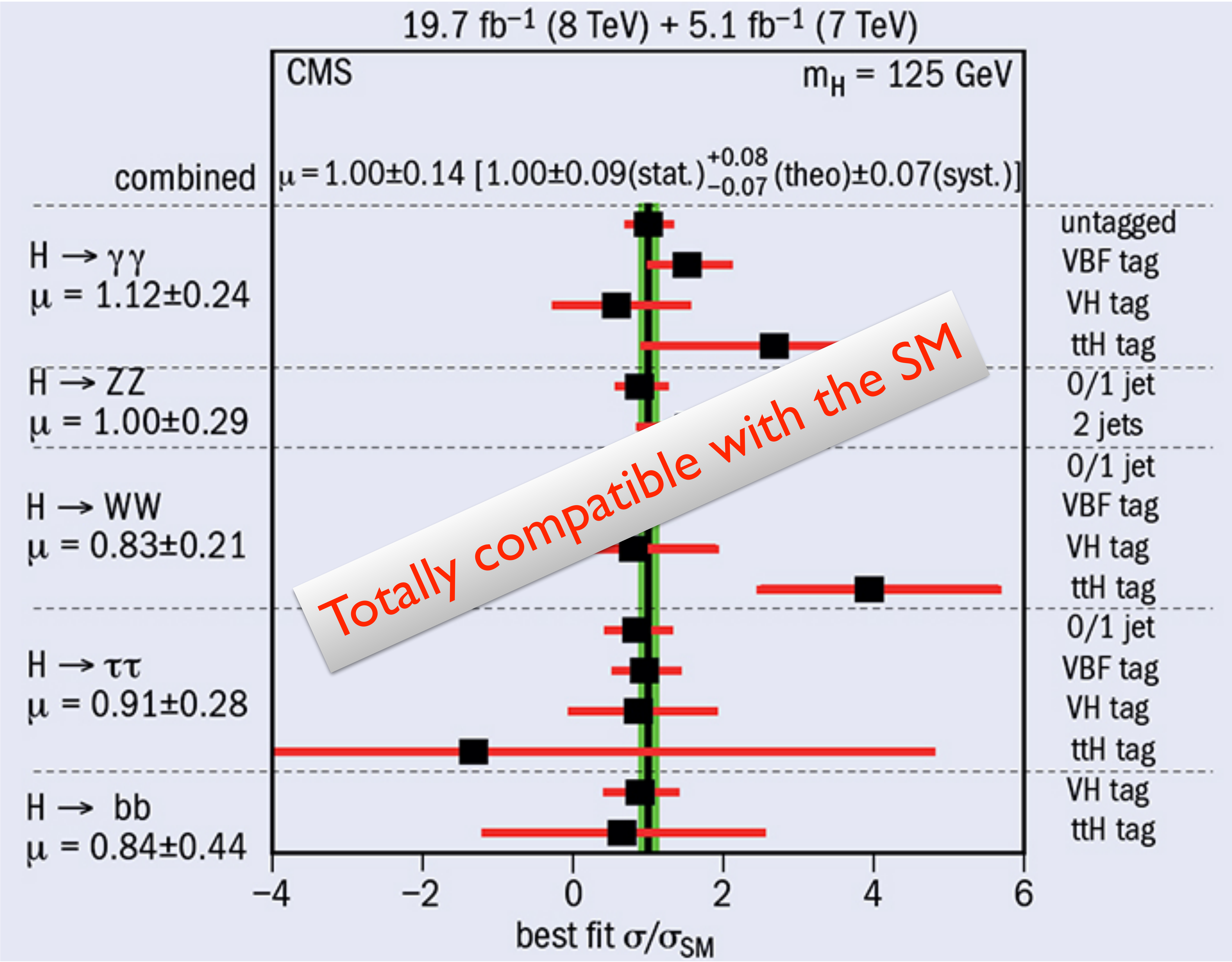

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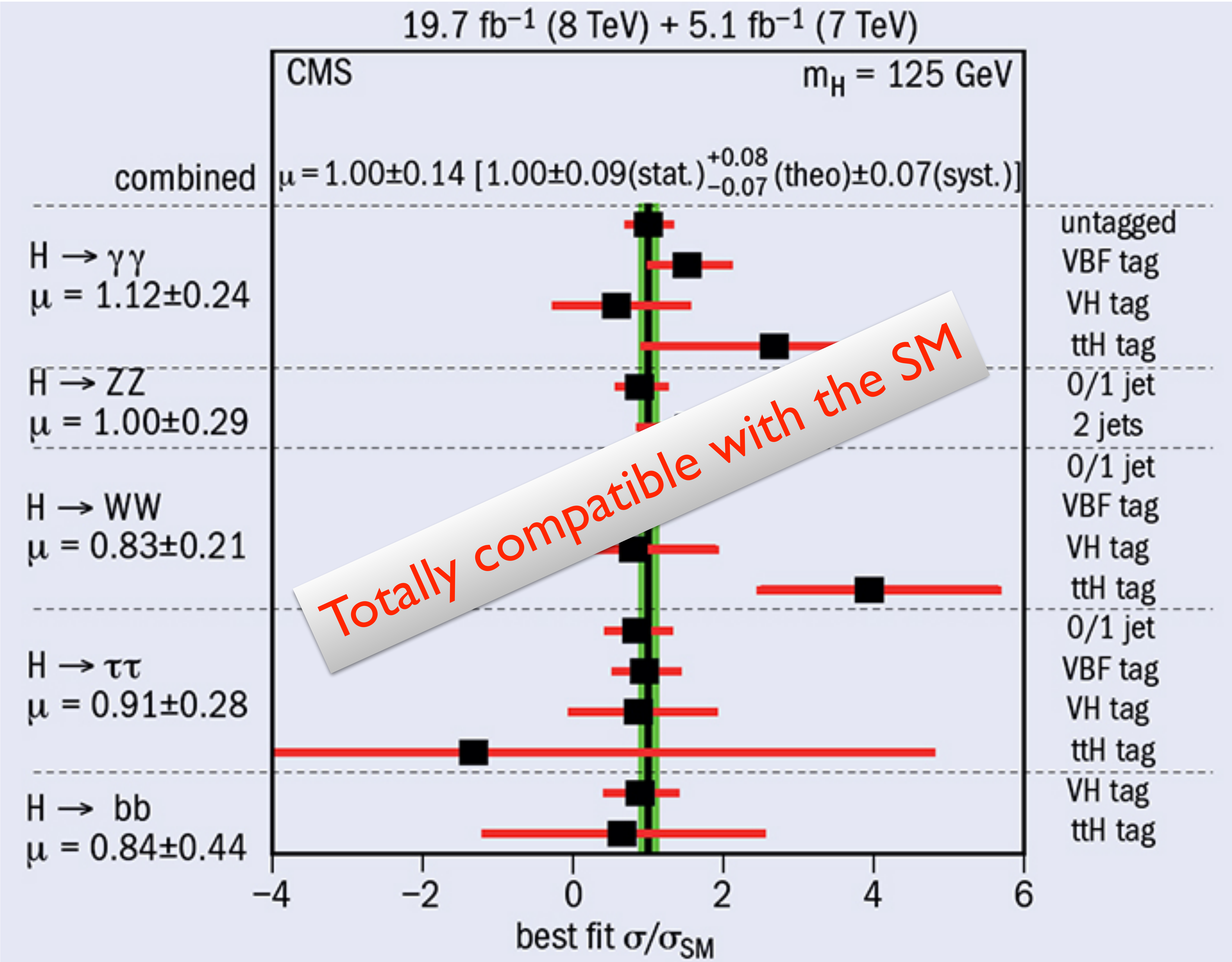

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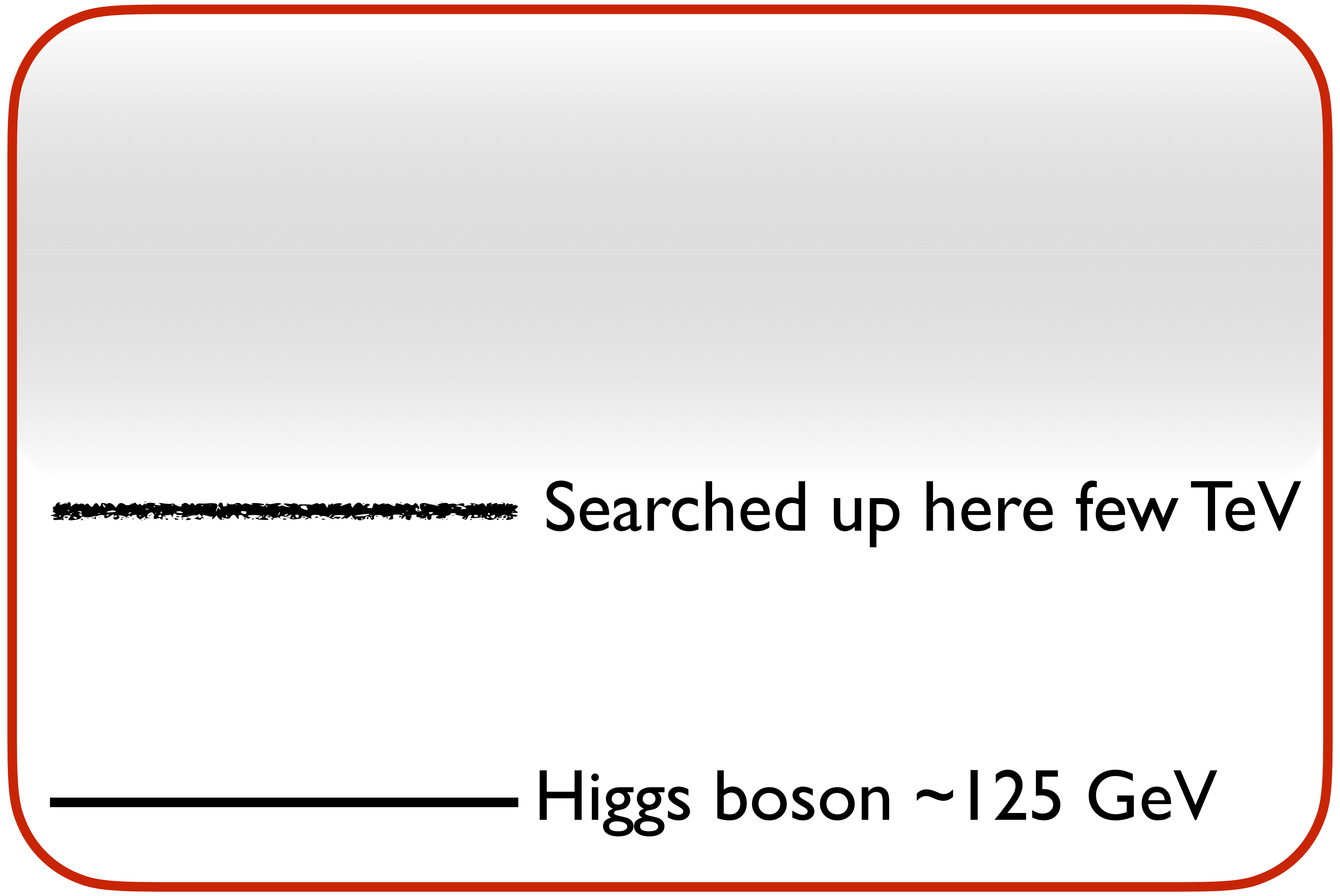


Why is the Higgs boson so light?

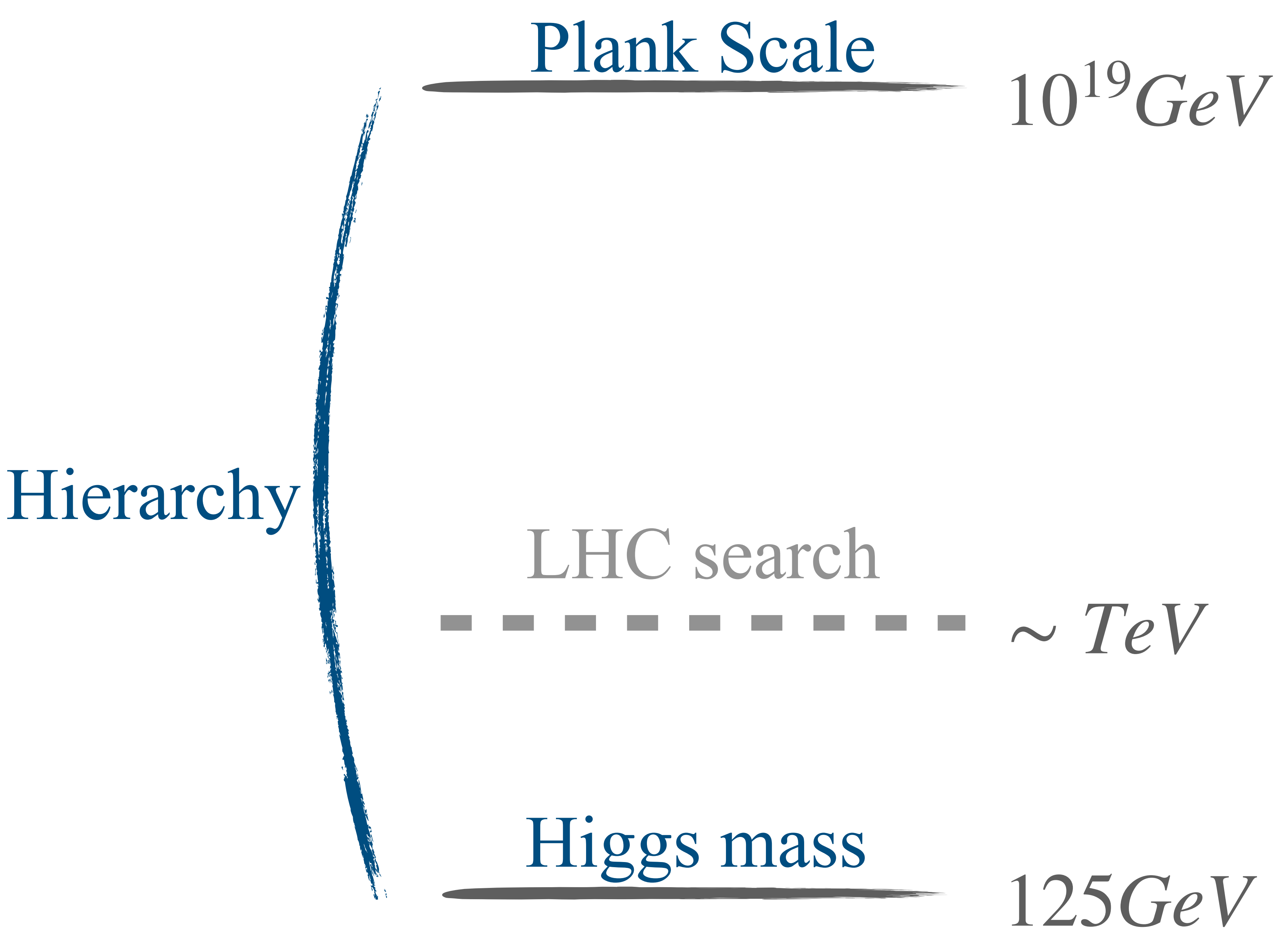
Lesson from QCD

Plank Scale $10^{19} GeV$

Hierarchy

Higgs mass $125 GeV$

Lesson from QCD



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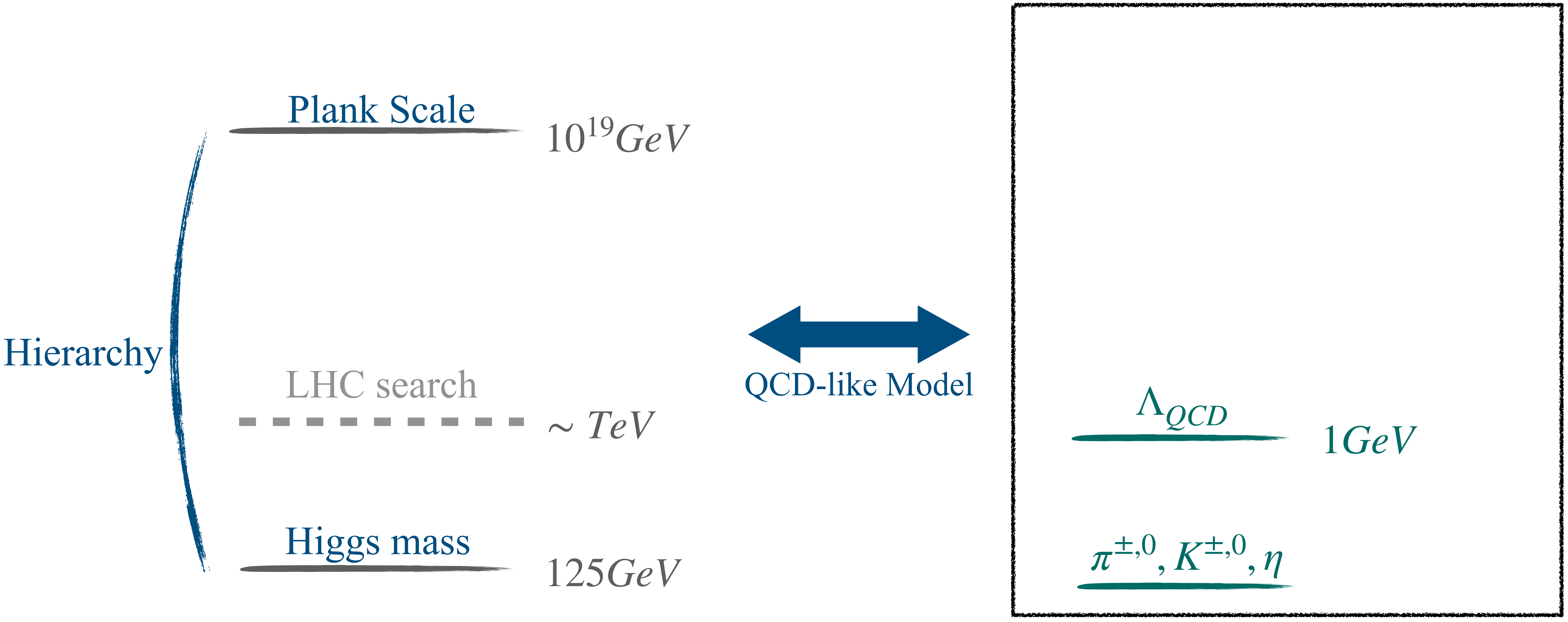

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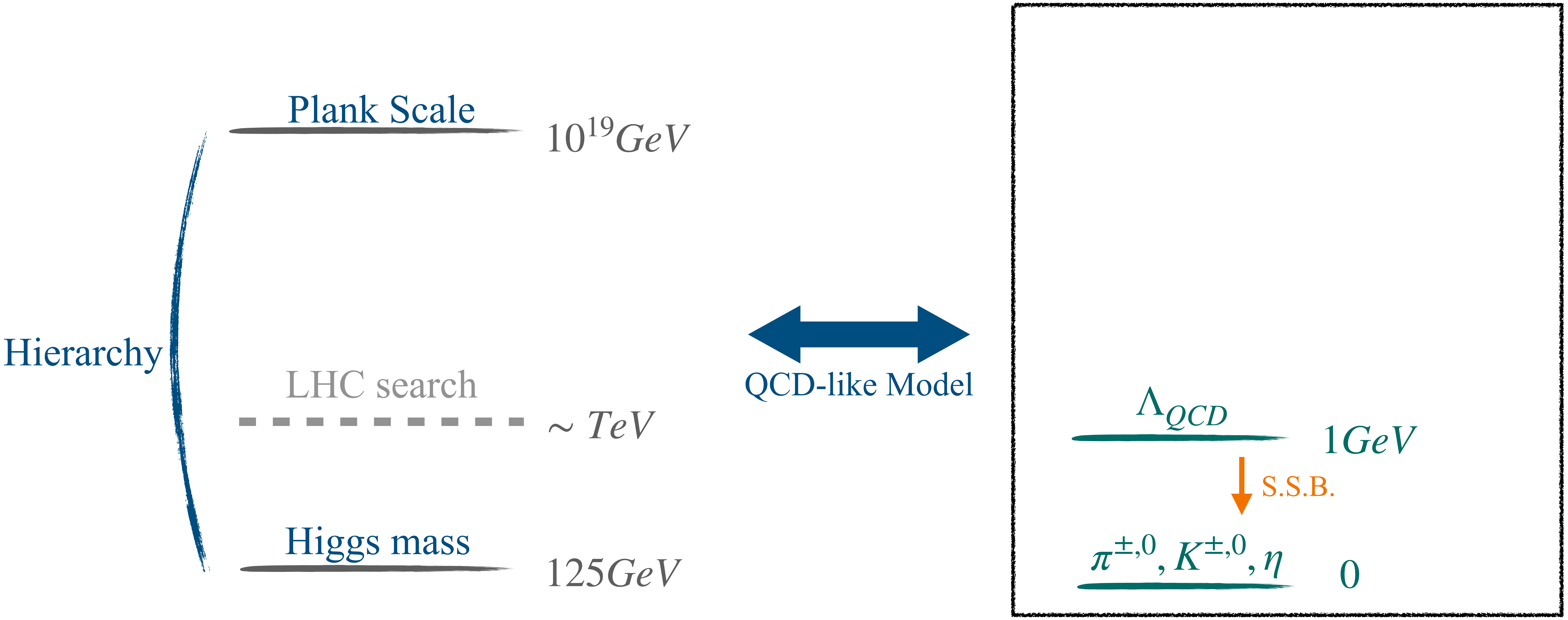

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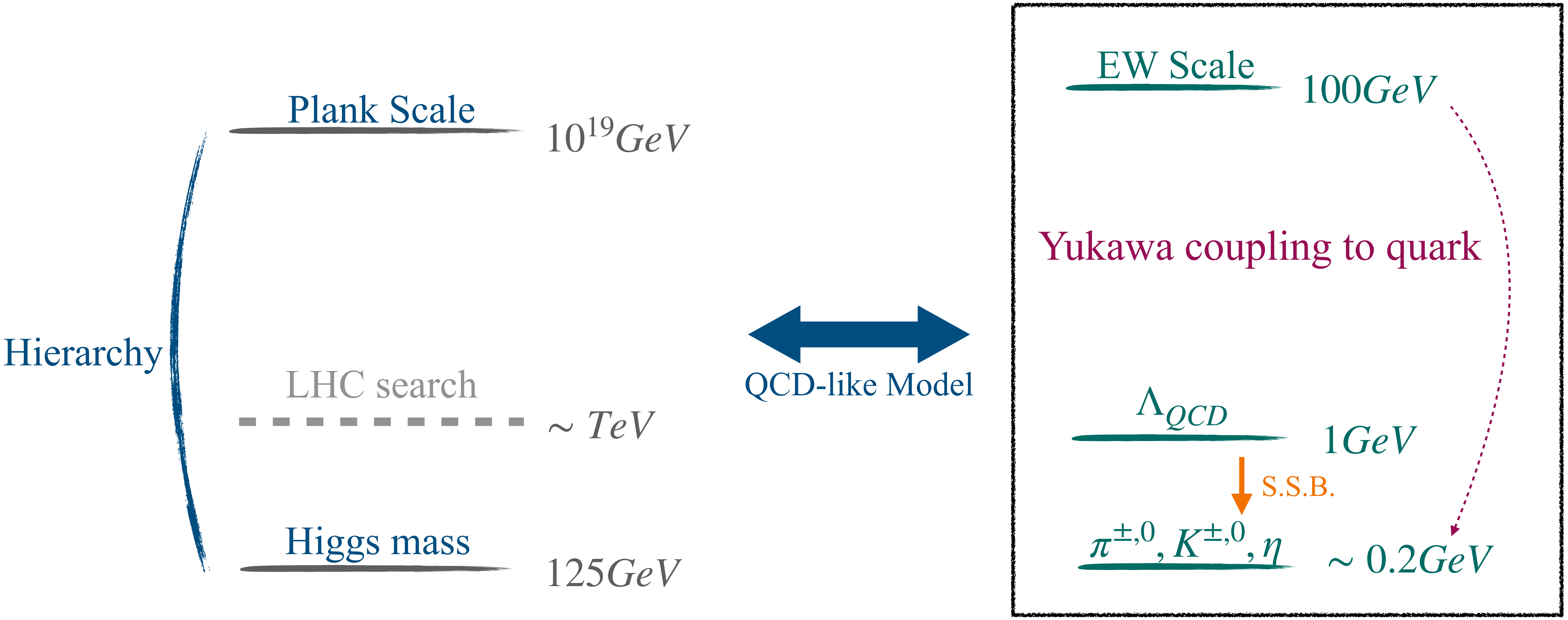

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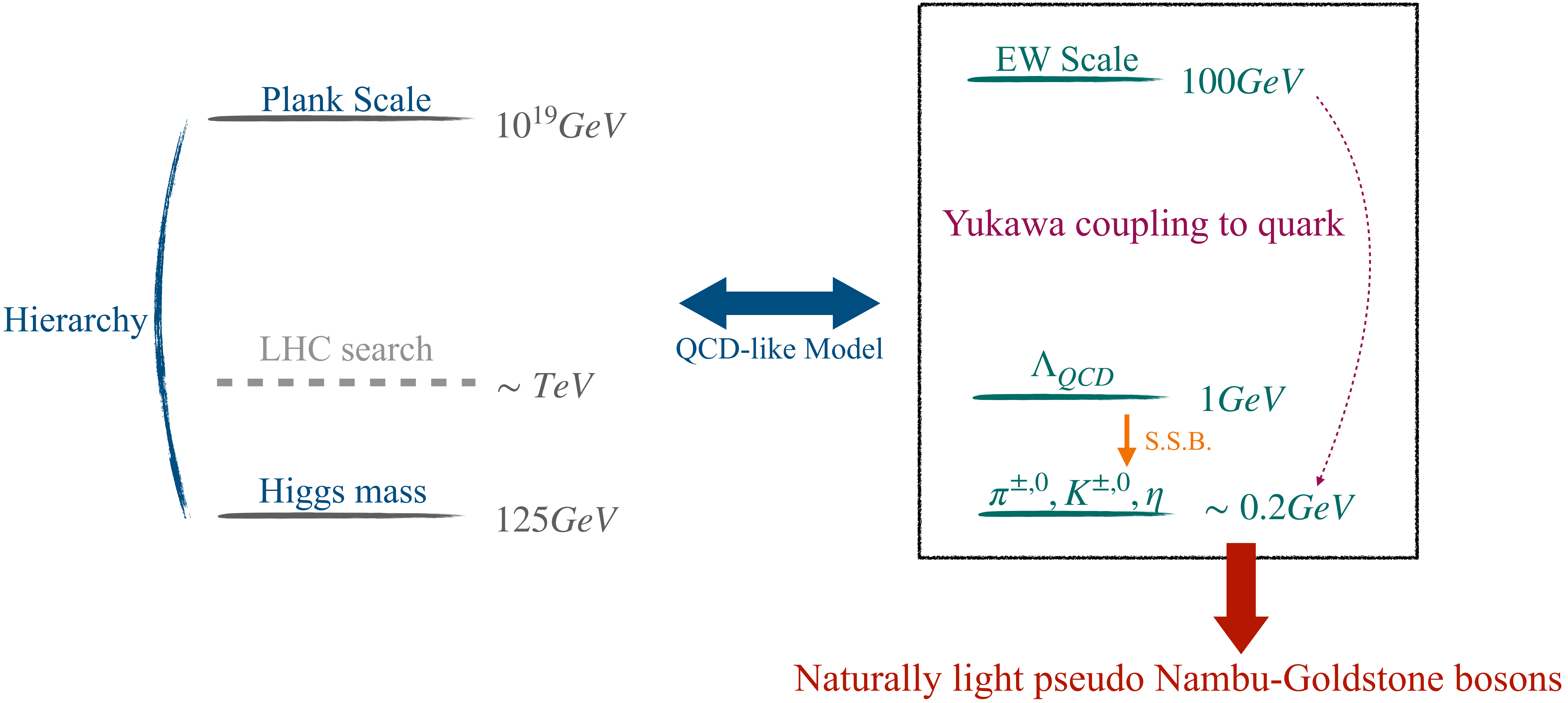
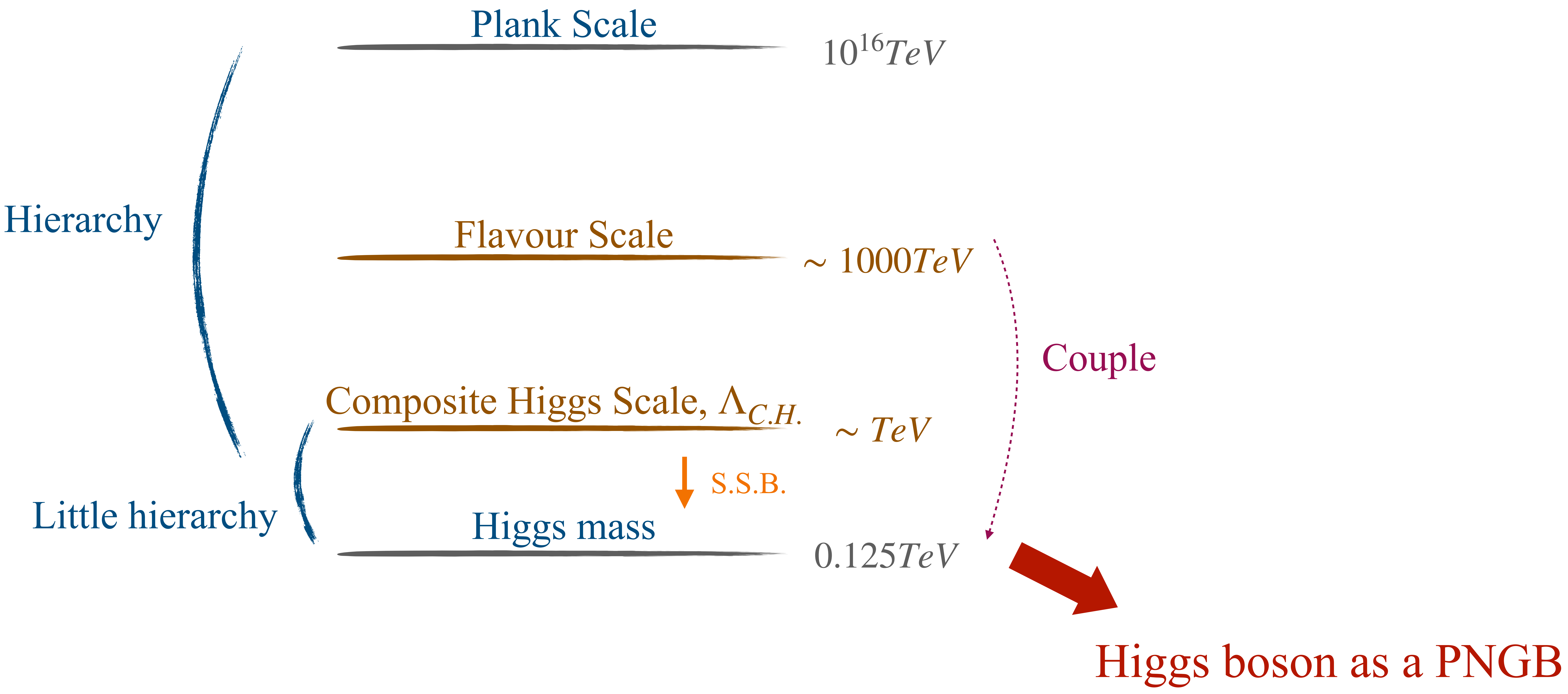


Composite Higgs models: Hierarchy of scales



Composite Higgs models: Generic features

D.B. Kaplan, H. Georgi, M. Dugan, S. Dimopoulos,… *circa* 1985

- Global symmetry G broken to H
- Standard model global $G_W \subset H$
- The Higgs boson $\in G/H$
  → *c.f.*, technicolour where Higgs $\in H$
- Higgs mass generated *via* vacuum misalignment
  → $v << f\sin\langle\theta\rangle,\ f = |\vec{F}| \sim \Lambda_{HC}$
- Top-quark mass generated *via* partial compositeness
  → Spin-1/2 bound states mixing with top quark

D.B. Kaplan, 1991

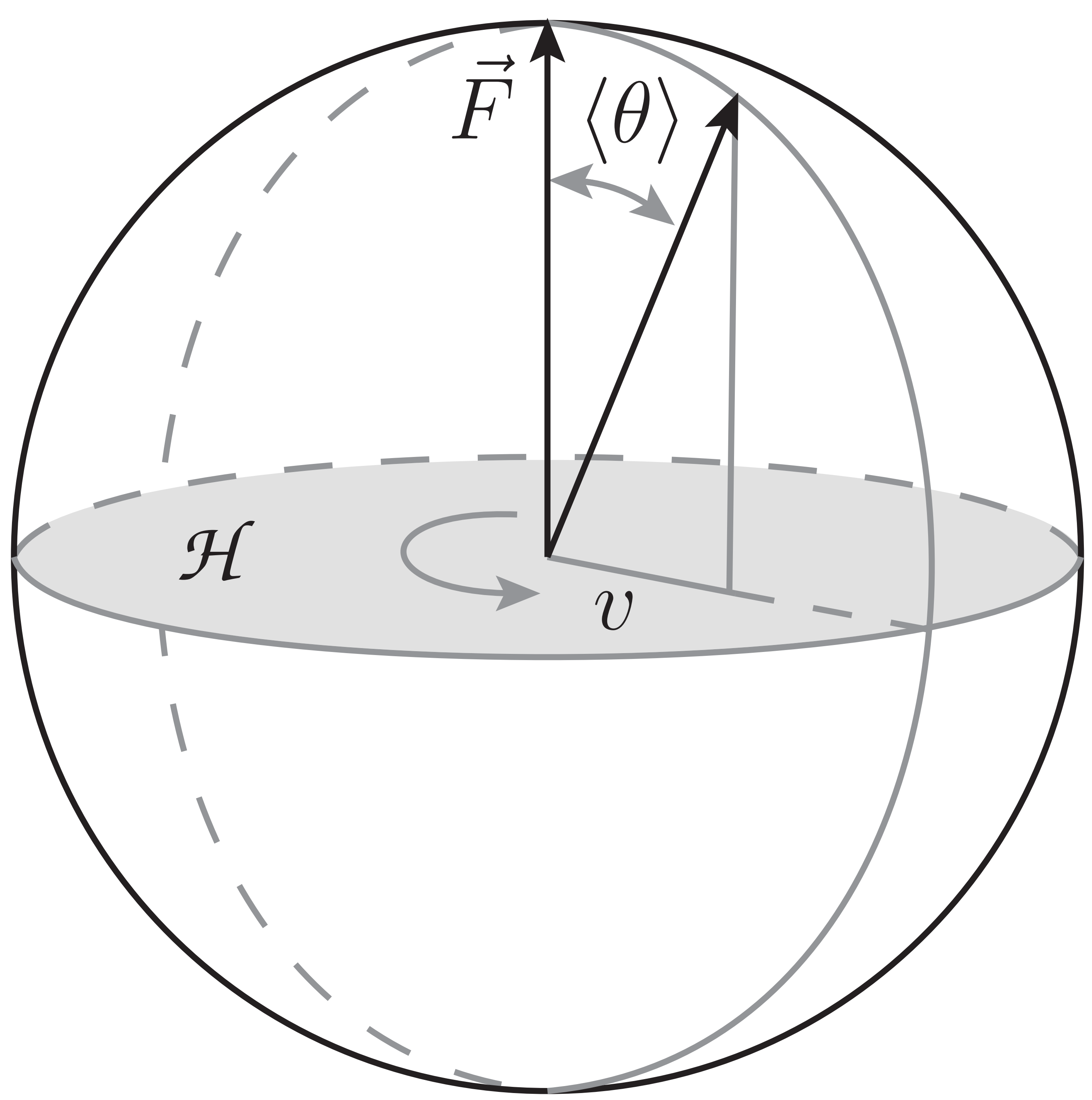


Figure from G. Panico and A. Wulzer, 1506.01961

UV completion of composite Higgs models

*Two-component relativistic fermions

Name	Gauge group	ψ	χ	Baryon type
M1	$SO(7)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\psi\chi\chi$
M2	$SO(9)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\psi\chi\chi$
M3	$SO(7)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$\psi\psi\chi$
M4	$SO(9)$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$\psi\psi\chi$
M5	$Sp(4)$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$\psi\chi\chi$
M6	$SU(4)$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$\psi\chi\chi$
M7	$SO(10)$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$\psi\chi\chi$
M8	$Sp(4)$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$\psi\psi\chi$
M9	$SO(11)$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$\psi\psi\chi$
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D. Franzosi and G. Ferretti, arXiv:1905.08273

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The minimal model
Barnard et al, arXiv:1311.6562

D. Franzosi and G. Ferretti, arXiv:1905.08273

Fermion representations and global symmetry

M. Peskin, 1980

For N_f flavours of Dirac fermions

Gauge group representation	Global symmetry breaking pattern
Complex	$SU(N_f) \times SU(N_f) \to SU(N_f)$
Real	$SU(2N_f) \to SO(2N_f)$
Pseudo-real	$SU(2N_f) \to Sp(2N_f)$

Our choice of model

- Sp(4) gauge theory with 2F+3AS Dirac fermions

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- $SU(4)/Sp(4)$ gives 5 goldstone bosons.
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  - 1: made heavy in model building

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- SU(3) embedded in antisymmetric representation:

$$SU(6) \to SO(6) \supset SU(3)$$

↳ QCD colour SU(3)

The low-lying chimera baryon states

- Interpolating operators
  - Λ type: $\mathcal{O}_{\mathrm{CB},\gamma^5} = \left(\bar{\psi}^{1\,a}\gamma^5\psi^{2\,b}\right)\Omega_{bc}\chi^{k\,ca}$

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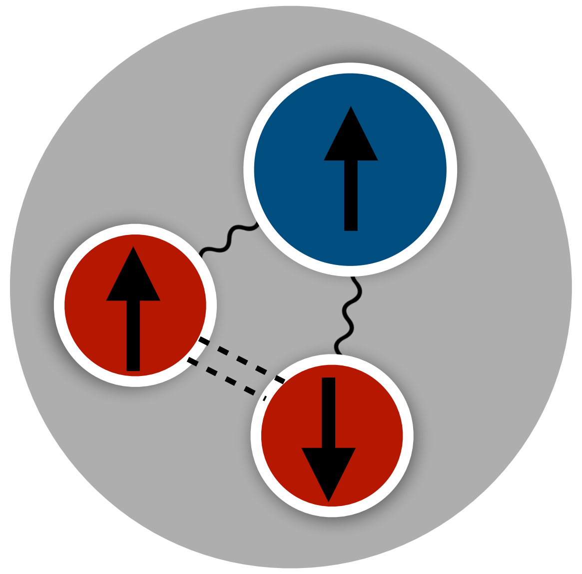

$(J, R) = (1/2, 5)$

a, b, c: hypercolour
Ω: 4×4 symplectic matrix
J: spin
R: irreducible rep. of the fundamental sector

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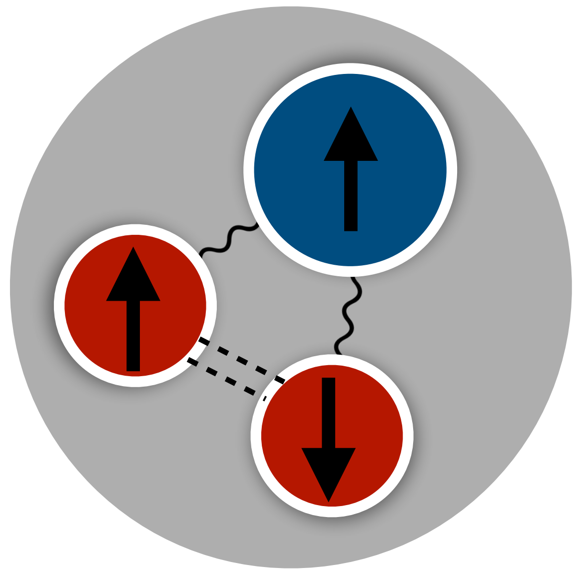

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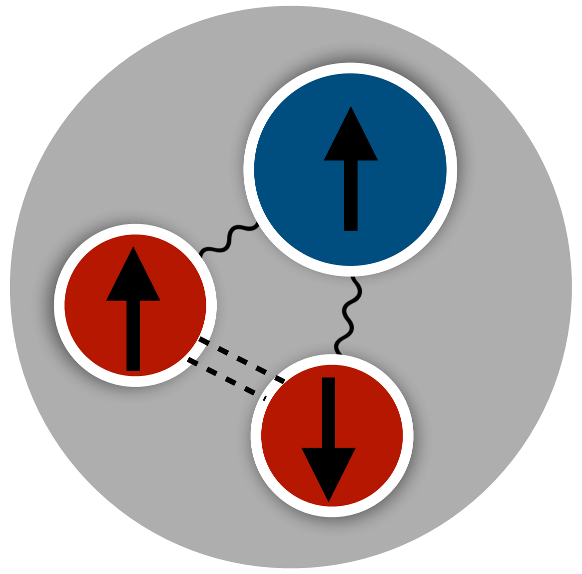

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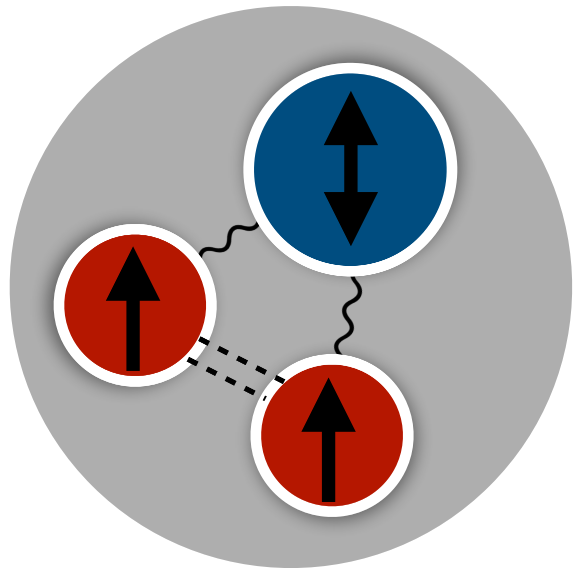

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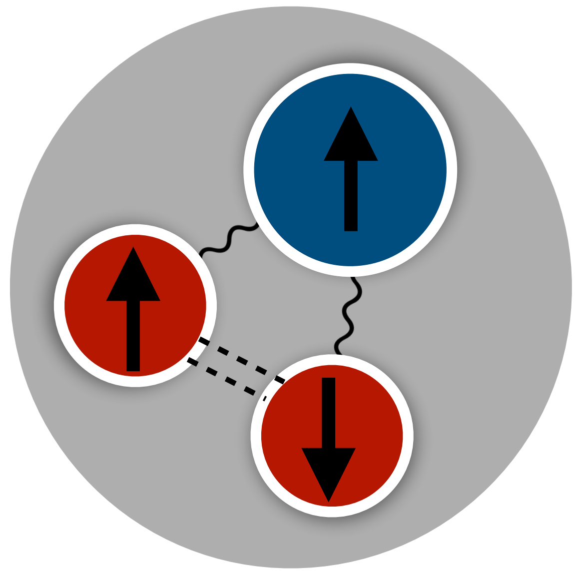

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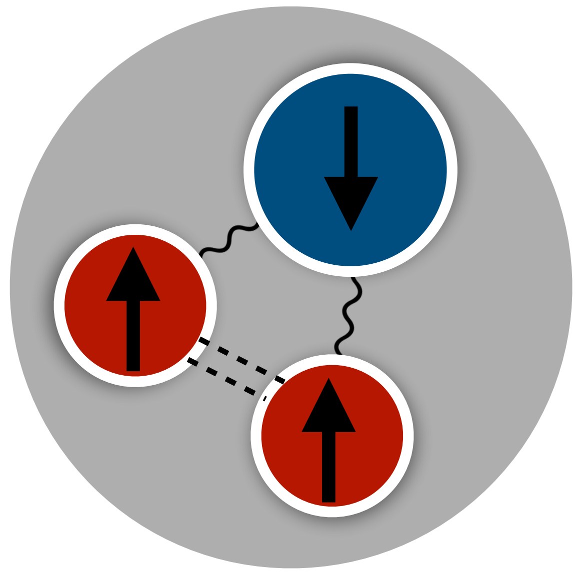

Σ: $(J, R) = (1/2, 10)$

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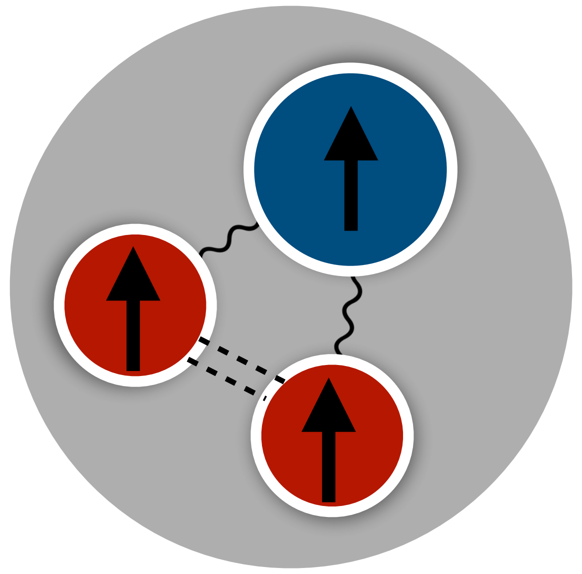
Spin projection



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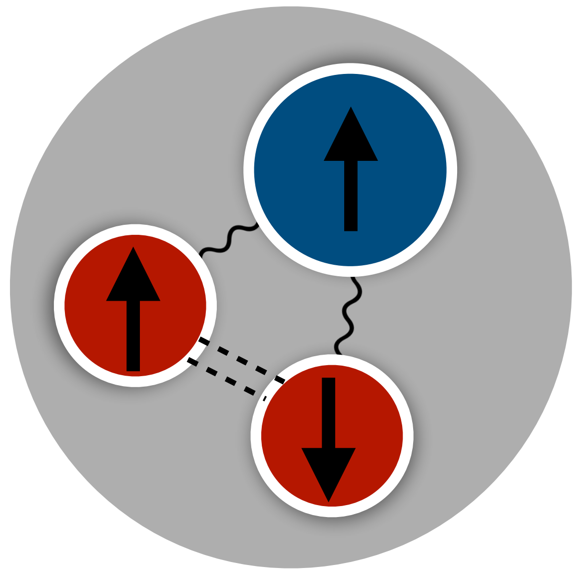

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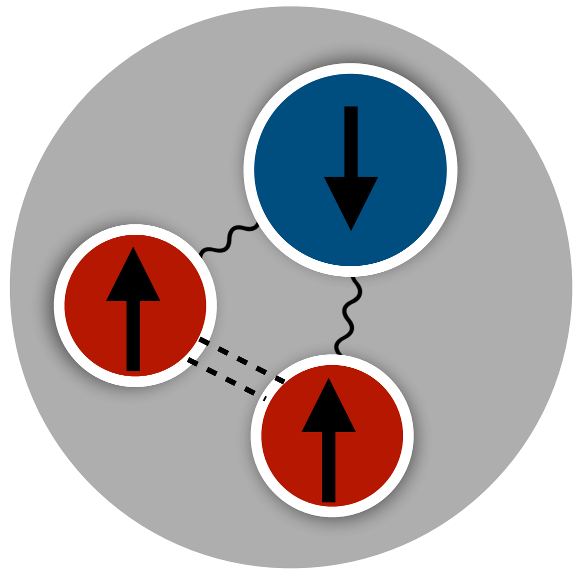

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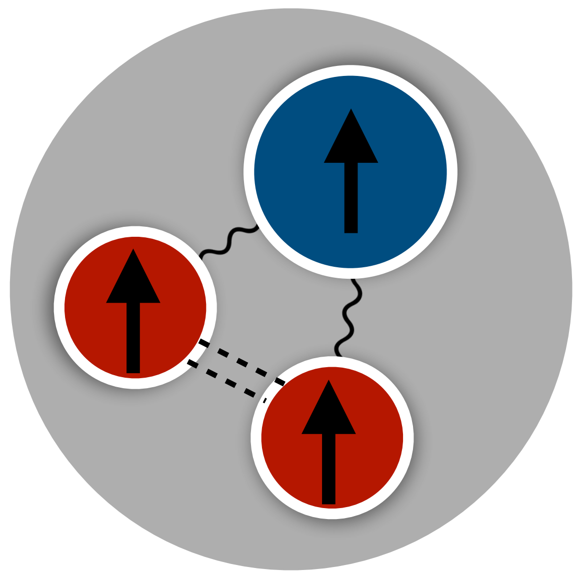

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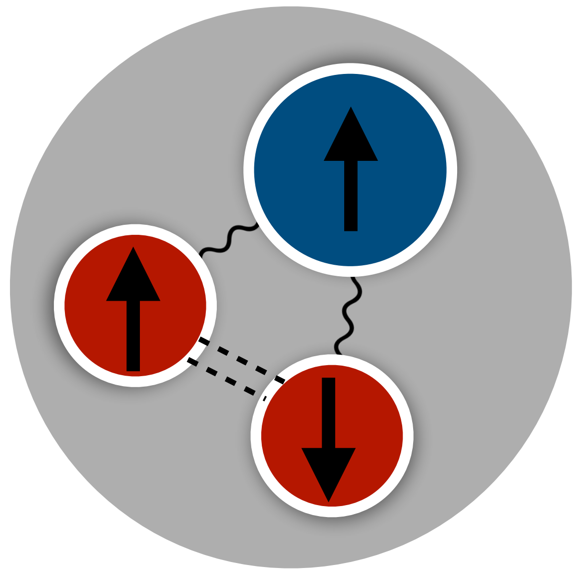

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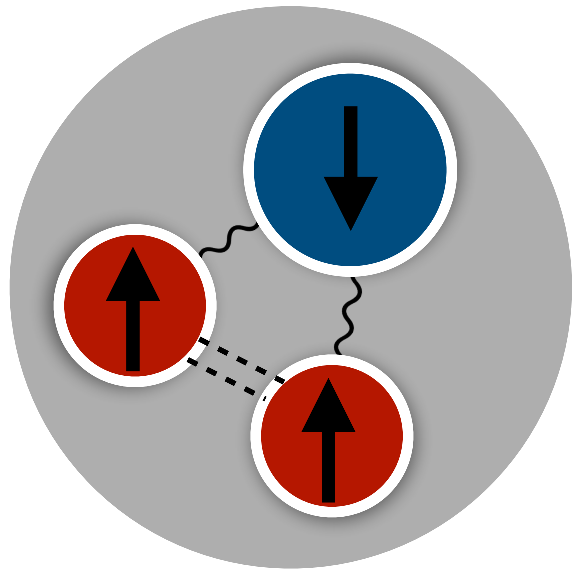

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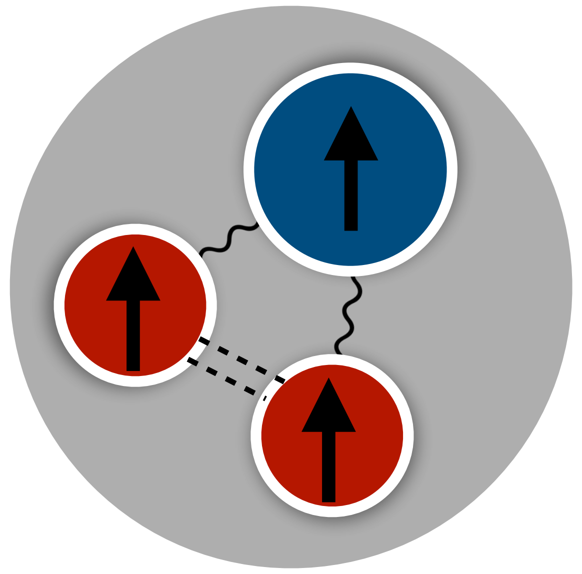


Σ^*: $(J, R) = (3/2, 10)$

$m_{\mathrm{top}} \sim 1/m_{\mathrm{CB}}$

Lattice studies of Sp(4) gauge theory

Major works from our collaboration

Sp(4) gauge [1712.04220]

Review:
Sp(2N) [2304.01070]

- Meson [1911.00437]
- Singlet [2304.07191]

Fund. $N_f = 2$

- Meson [2210.08154]

Anti. $n_f = 3$

Quenched

- F. and AS. Meson spectra [1712.04220,1912.06505]
- Glueball [2010.15781]
- Topology [2205.09254, 2205.09364]
- Chimera baryon [2311.14663]
- large-N meson [2312.08465]

Fully dynamical

- Parameter scan[2202.05516]
- GRID with Sp(2N) [2306.11649]
- Singlet meson [2405.05765]
- Spectral densities [2405.01388]

Quenched chimera baryons

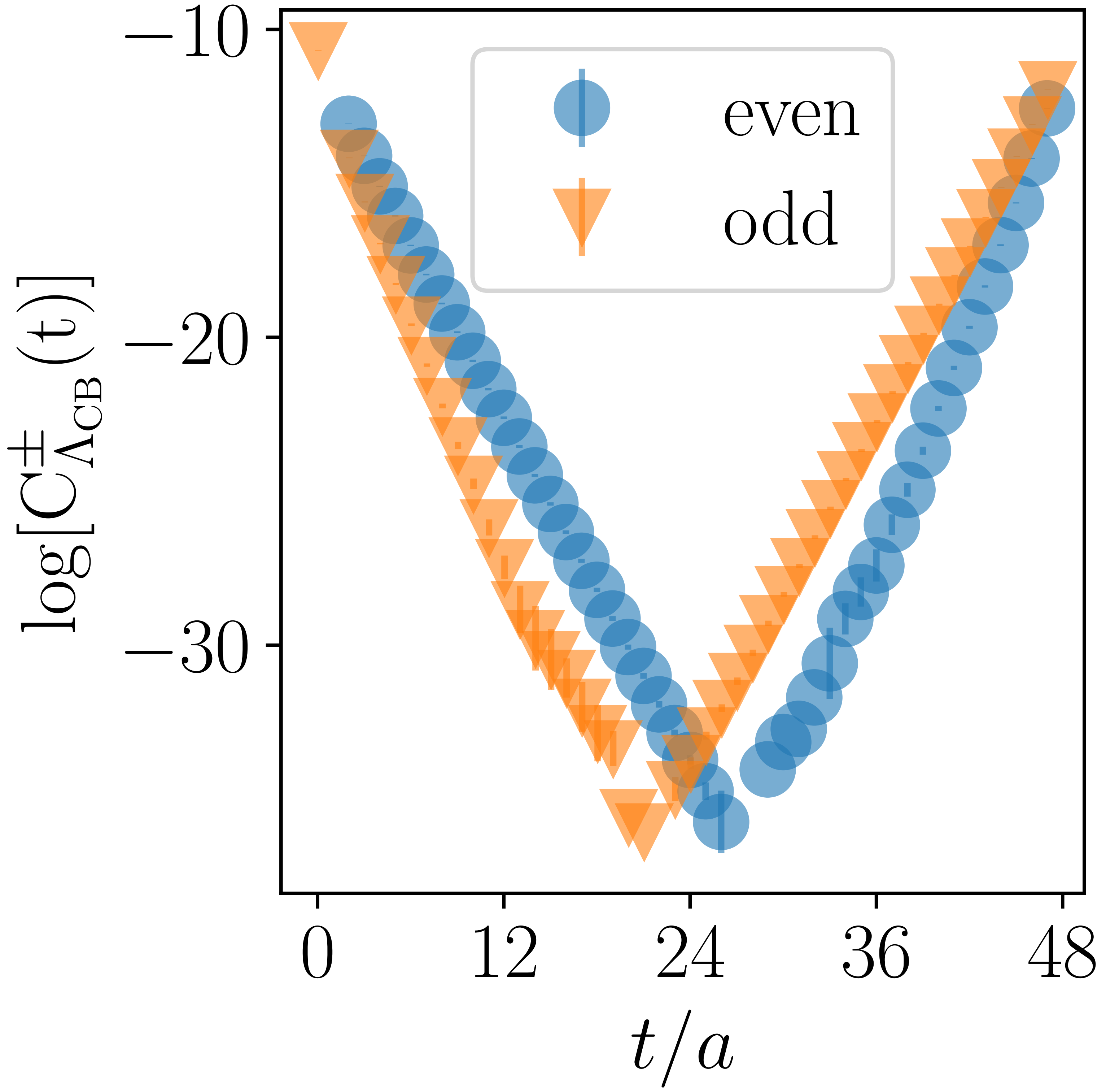
- Scan of parameter space
- Wilson plaquette and Wilson fermion actions

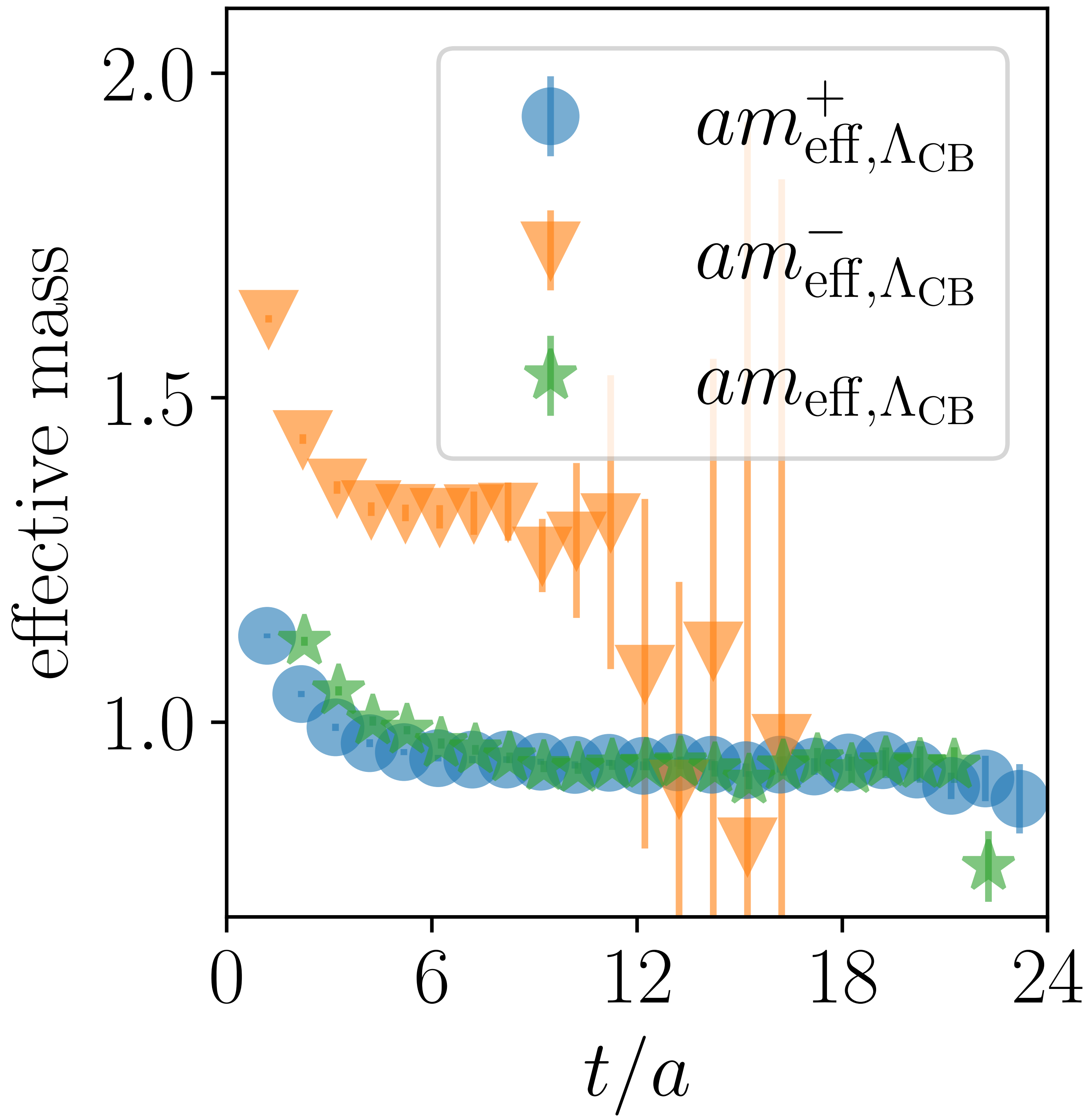
Ensemble	β	$N_t \times N_s^3$	$\langle P \rangle$	w_0/a
QB1	7.62	48×24^3	0.6018898(94)	1.448(3)
QB2	7.7	60×48^3	0.6088000(35)	1.6070(19)
QB3	7.85	60×48^3	0.6203809(28)	1.944(3)
QB4	8.0	60×48^3	0.6307425(27)	2.3149(12)
QB5	8.2	60×48^3	0.6432302(25)	2.8812(21)

Parity partners: who is lighter?

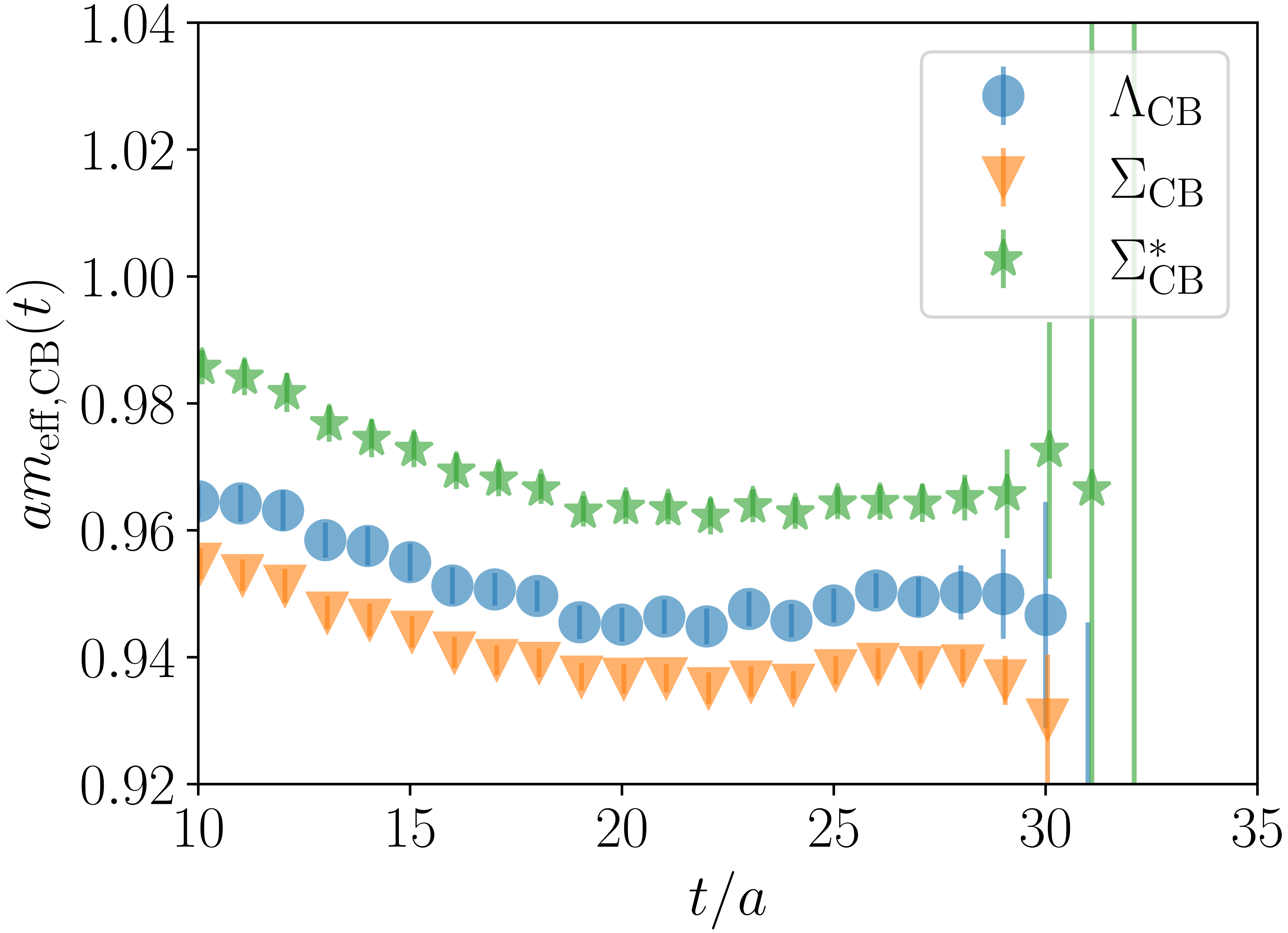
$$C_{\rm CB}(t) \xrightarrow{0 \ll t \ll T} P_+ \left[c_+ e^{-m^+ t} - c_- e^{-m^-(T-t)} \right] + P_- \left[c_- e^{-m^- t} - c_+ e^{-m^+(T-t)} \right]$$

$$C^{\pm}_{\rm CB}(t) \equiv P_{\pm}\, C_{\rm CB}(t)$$





Typical mass hierarchy



- Λ_{CB} is not lighter than Σ_{CB}
- *c.f.*, QCD where $m_\Lambda < m_\Sigma$

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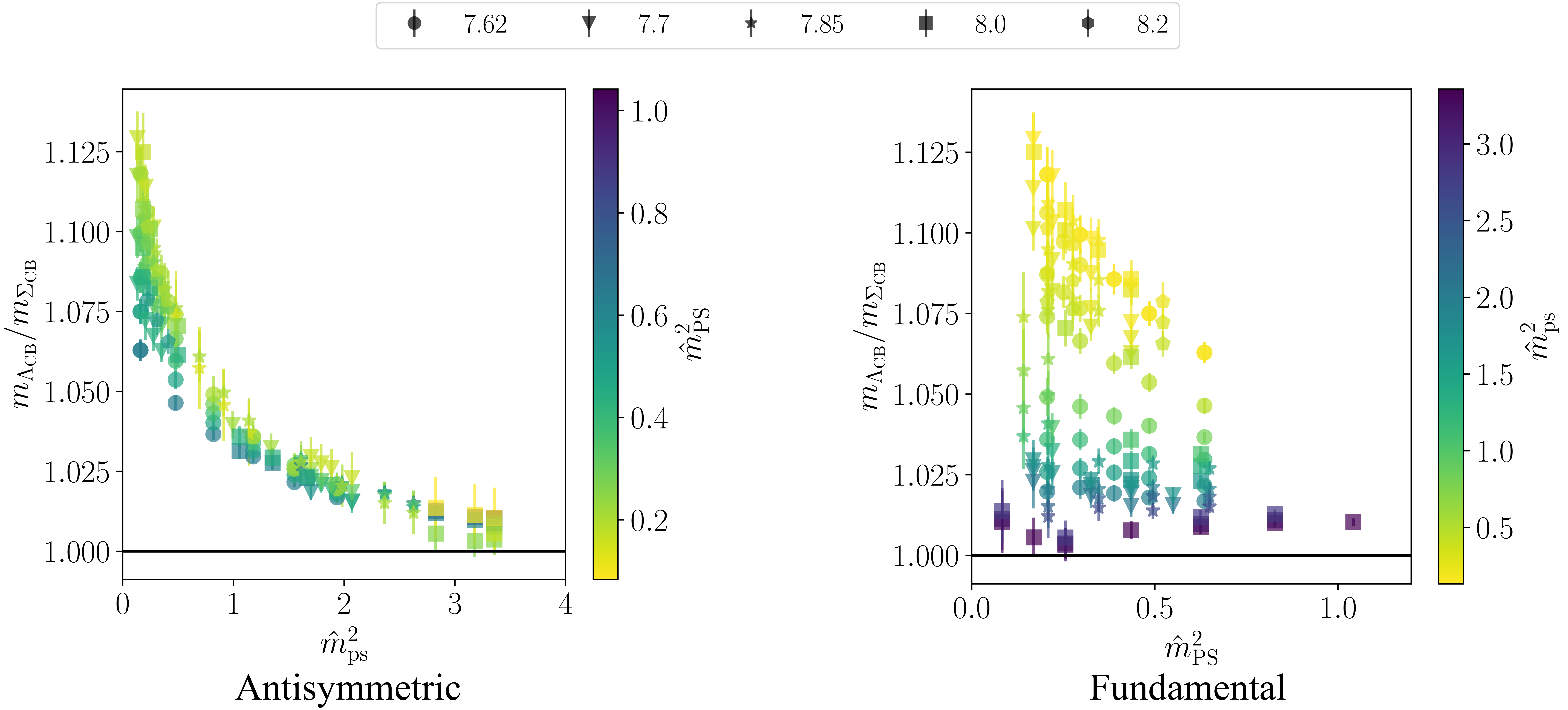

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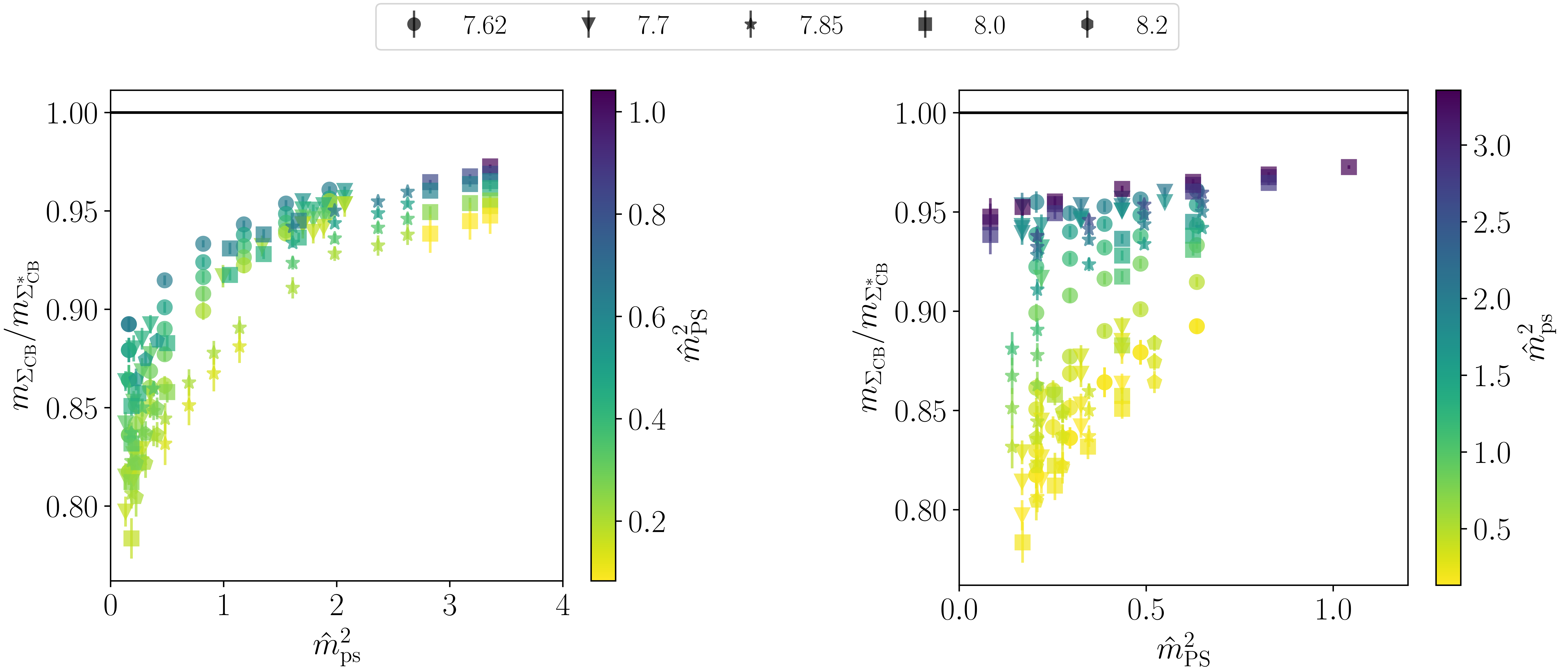
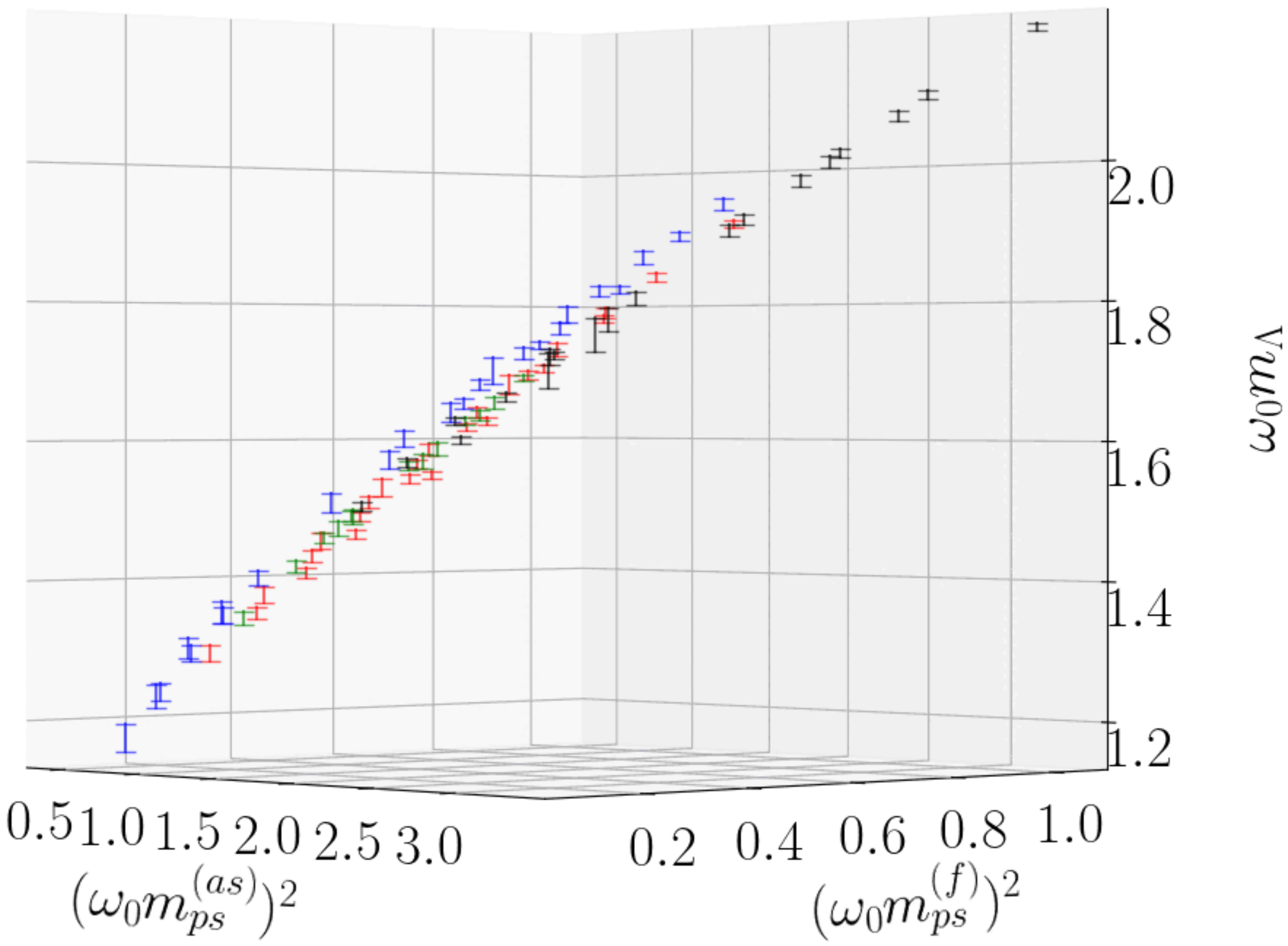


Antisymmetric

Fundamental

Hyperquark mass dependence



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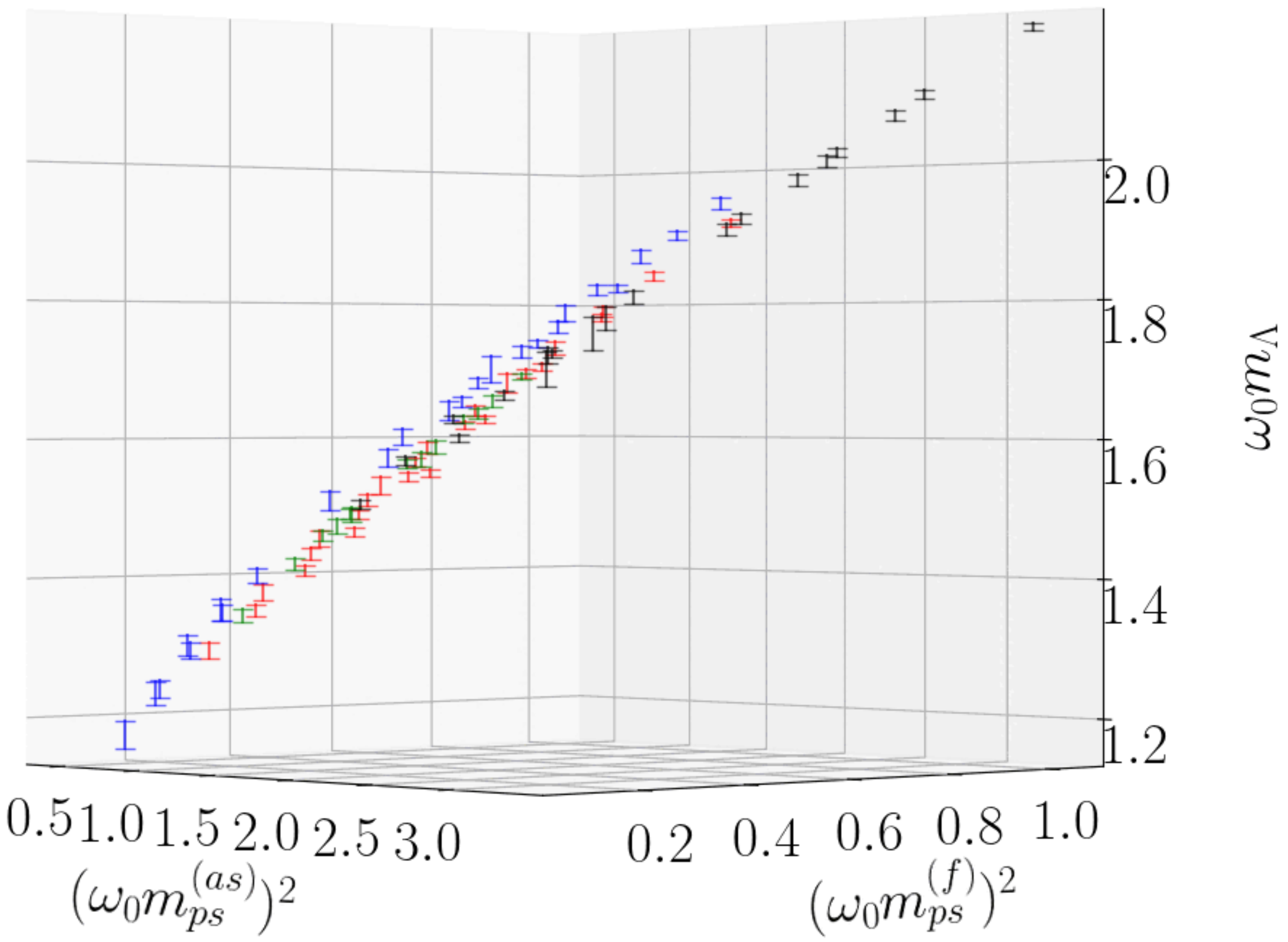
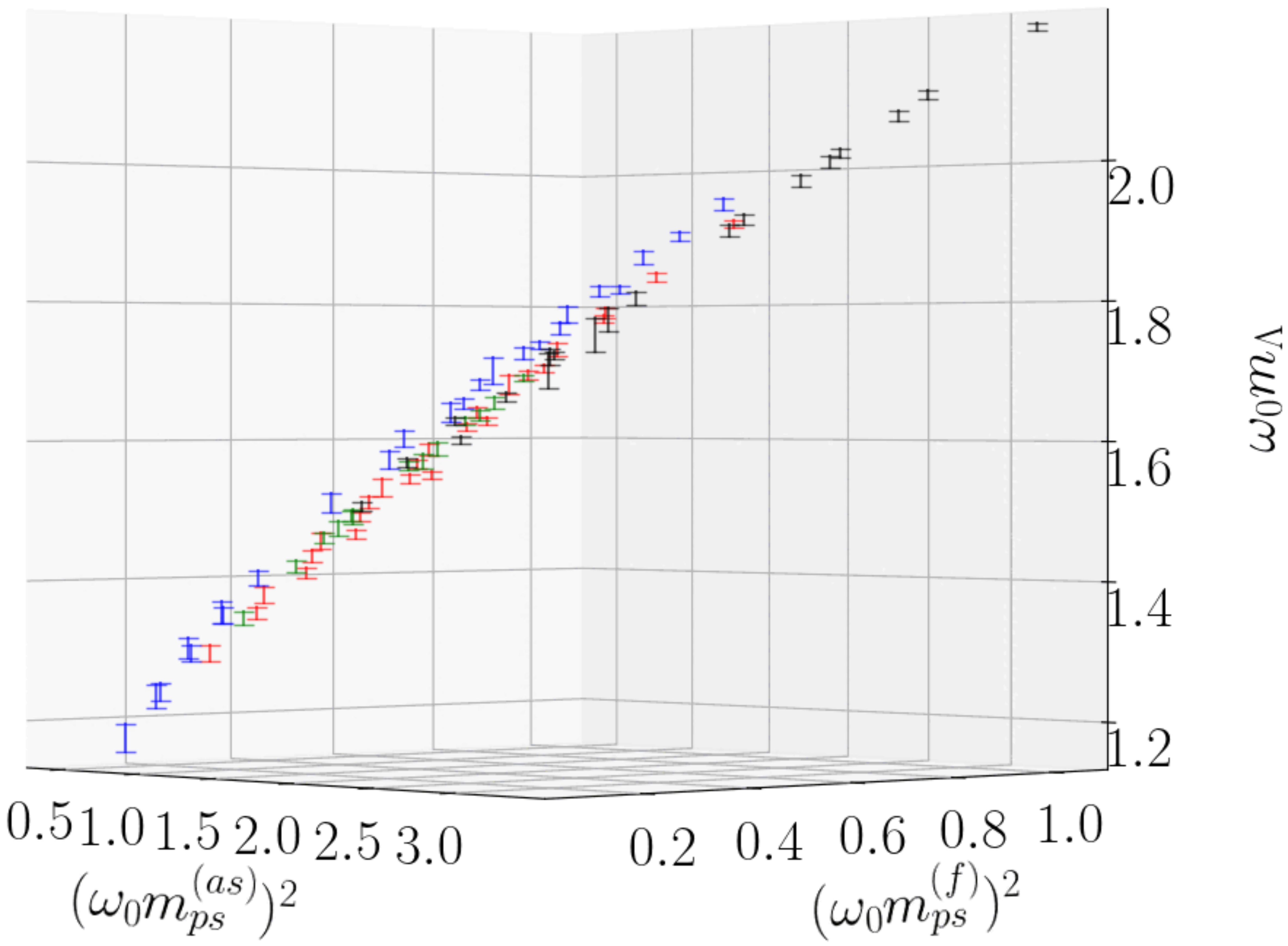


Hyperquark mass dependence

- Fit to analytic terms in baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m^{\chi}_{CB} + F_2\hat{m}^2_{\mathrm{PS}} + A_1\hat{m}_{\mathrm{ps}}{}^2 + L_1\hat{a} + F_3\hat{m}^3_{\mathrm{PS}} + A_3\hat{m}^3_{\mathrm{ps}} + L_{2F}\hat{a}\hat{m}^2_{\mathrm{PS}} + L_{2A}\hat{a}\hat{m}^2_{\mathrm{ps}} + F_4\hat{m}^4_{\mathrm{PS}} + A_4\hat{m}^4_{\mathrm{ps}} + C_4\hat{m}^2_{\mathrm{PS}}\hat{m}^2_{\mathrm{ps}}$$



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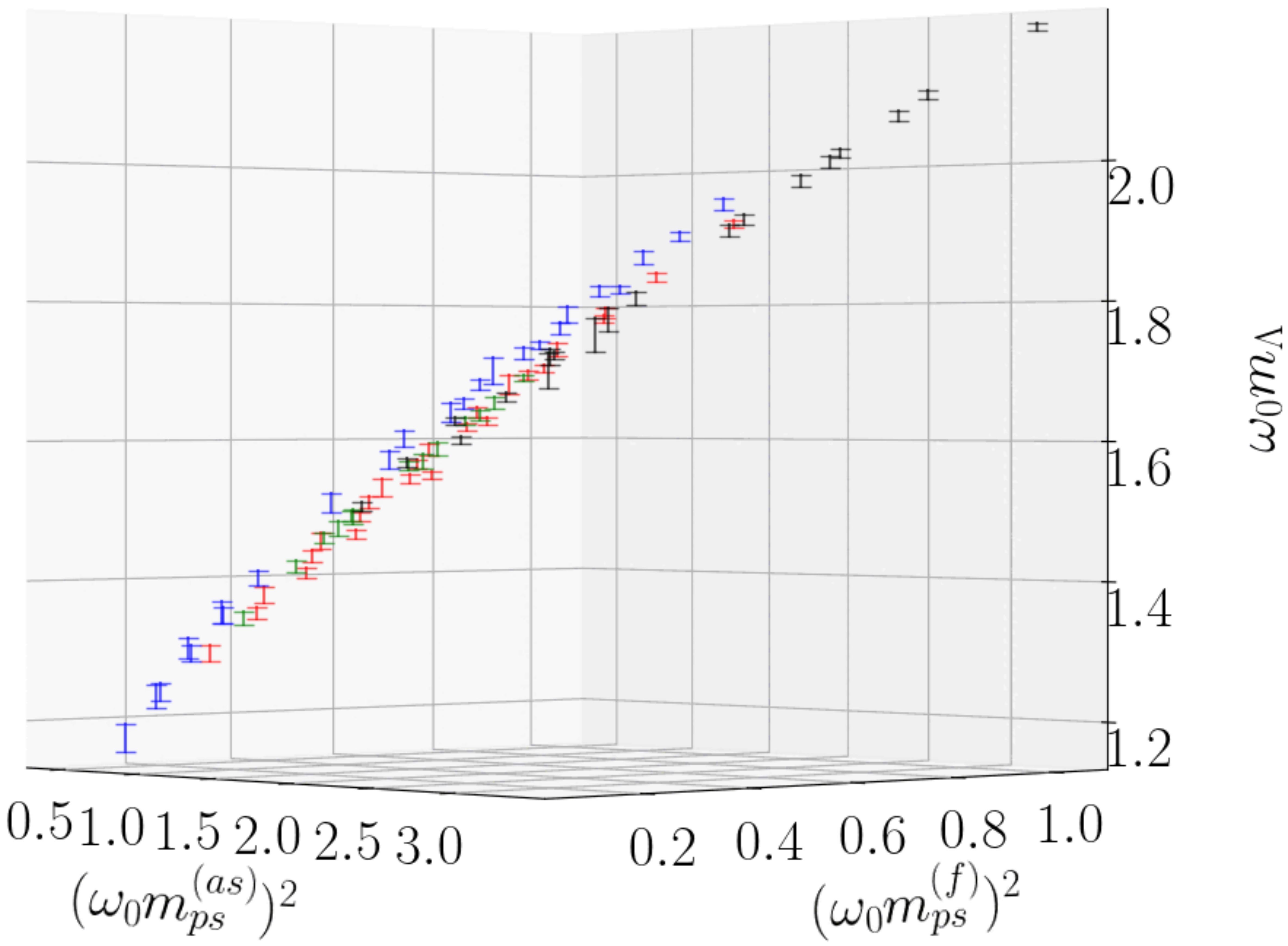
- Cannot obtain stable fits

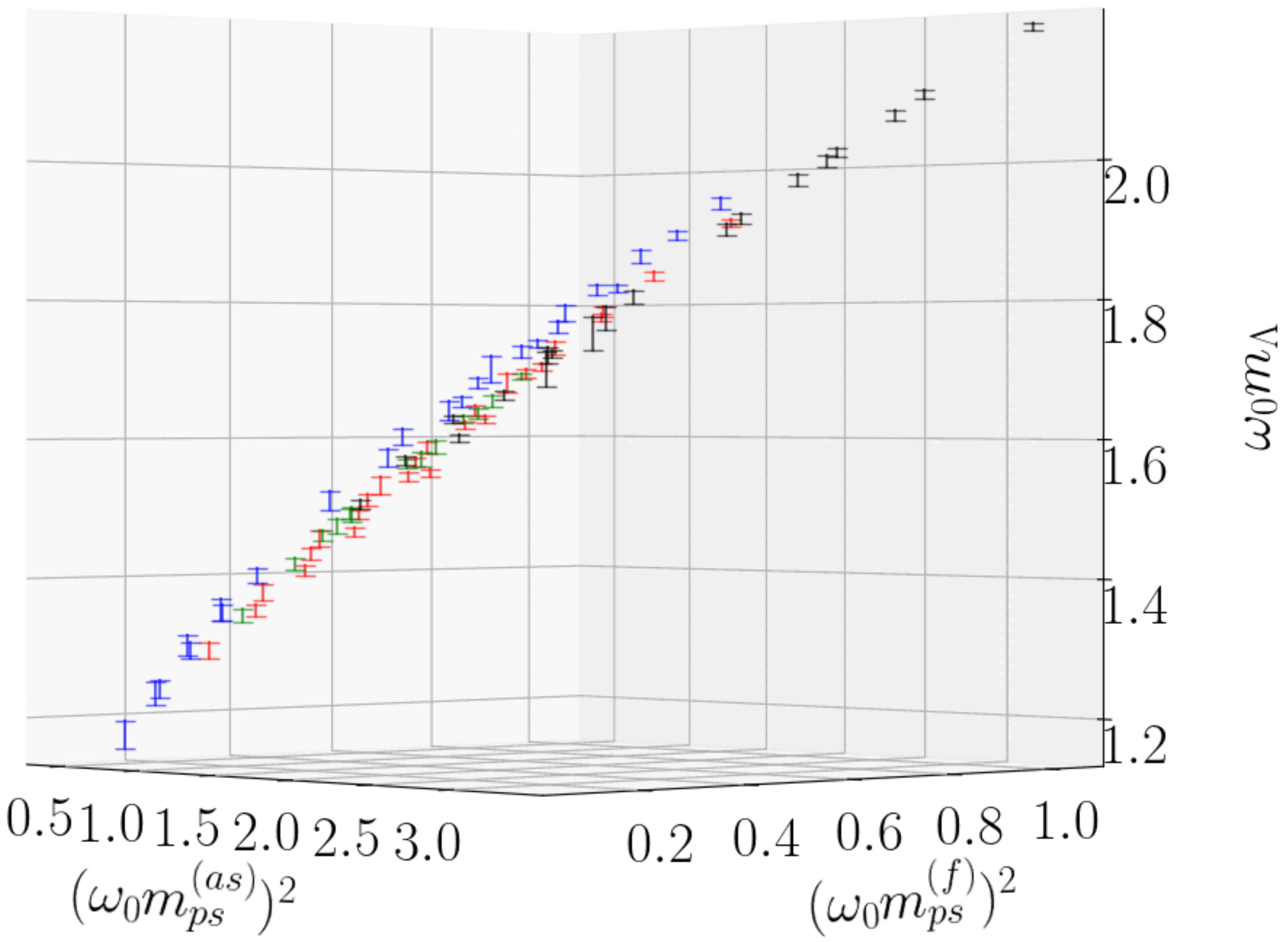


Hyperquark mass dependence

- Fit to analytic terms in baryon chiral perturbation theory

$$m_{\rm CB} = m_{CB}^{\chi} + F_2\hat{m}_{\rm PS}^2 + A_1\hat{m}_{\rm ps}{}^2 + L_1\hat{a} + F_3\hat{m}_{\rm PS}^3 + A_3\hat{m}_{\rm ps}^3 + L_{2F}\hat{a}\hat{m}_{\rm PS}^2 + L_{2A}\hat{a}\hat{m}_{\rm ps}^2 + F_4\hat{m}_{\rm PS}^4 + A_4\hat{m}_{\rm ps}^4 + C_4\hat{m}_{\rm PS}^2\hat{m}_{\rm ps}^2$$

- Cannot obtain stable fits
- Removing heavy-mass data does not help



Hyperquark mass dependence

Hyperquark mass dependence

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$$+ F_3 \hat{m}_{\mathrm{PS}}^3 + A_3 \hat{m}_{\mathrm{ps}}^3 + L_{2F} \hat{a} \hat{m}_{\mathrm{PS}}^2 + L_{2A} \hat{a} \hat{m}_{\mathrm{ps}}^2$$
$$+ F_4 \hat{m}_{\mathrm{PS}}^4 + A_4 \hat{m}_{\mathrm{ps}}^4 + C_4 \hat{m}_{\mathrm{PS}}^2 \hat{m}_{\mathrm{ps}}^2$$

Hyperquark mass dependence

- Fit to analytic terms in baryon chiral perturbation theory

$$m_{\text{CB}} = m^{\chi}_{CB} + F_2 \hat{m}^2_{\text{PS}} + A_1 \hat{m}_{\text{ps}}{}^2 + L_1 \hat{a} \quad \text{- - - - - - - - - - M2}$$

$$+ F_3 \hat{m}^3_{\text{PS}} + A_3 \hat{m}^3_{\text{ps}} + L_{2F} \hat{a} \hat{m}^2_{\text{PS}} + L_{2A} \hat{a} \hat{m}^2_{\text{ps}}$$

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Hyperquark mass dependence

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$$+ F_4\hat{m}^4_{\rm PS} + A_4\hat{m}^4_{\rm ps} + C_4\hat{m}^2_{\rm PS}\hat{m}^2_{\rm ps}$$

Hyperquark mass dependence

- Fit to analytic terms in baryon chiral perturbation theory

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$$\underbrace{+ F_4 \hat{m}_{\text{PS}}^4}_{\text{MF4}} + A_4 \hat{m}_{\text{ps}}^4 + C_4 \hat{m}_{\text{PS}}^2 \hat{m}_{\text{ps}}^2$$

Hyperquark mass dependence

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Hyperquark mass dependence

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$$\underbrace{+ F_4\hat{m}^4_{\rm PS}}_{\text{MF4}} \underbrace{+ A_4\hat{m}^4_{\rm ps}}_{\text{MA4}} \underbrace{+ C_4\hat{m}^2_{\rm PS}\hat{m}^2_{\rm ps}}_{\text{MC4}}$$

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Fit Ansatz	$\hat{m}^{\chi}_{\rm CB}$	$\hat{m}^2_{\rm PS}$	$\hat{m}^2_{\rm ps}$	$\hat{m}^3_{\rm PS}$	$\hat{m}^3_{\rm ps}$	$\hat{m}^4_{\rm PS}$	$\hat{m}^4_{\rm ps}$	$\hat{m}^2_{\rm PS}\hat{m}^2_{\rm ps}$	$\hat{a}$	$\hat{m}^2_{\rm PS}\hat{a}$	$\hat{m}^2_{\rm ps}\hat{a}$
M2	✓	✓	✓	-	-	-	-	-	✓	-	-
M3	✓	✓	✓	✓	✓	-	-	-	✓	✓	✓
MF4	✓	✓	✓	✓	✓	✓	-	-	✓	✓	✓
MA4	✓	✓	✓	✓	✓	-	✓	-	✓	✓	✓
MC4	✓	✓	✓	✓	✓	-	-	✓	✓	✓	✓

Procedures for the hyper quark-mass extrapolation

- Try the five fit ansatze

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- Systematically include data points with $am_{\mathrm{PS}} < 1$ and $am_{\mathrm{ps}} < 1$

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- $263 \times 5 = 1315$ analysis procedures

Procedures for the hyper quark-mass extrapolation

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- For each procedure, compute $\mathrm{AIC} \equiv \chi^2 + 2k + 2N_{\rm cut}$

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  (k: # of fit parameters)

Procedures for the hyper quark-mass extrapolation

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  → 263 data sets
- $263 \times 5 = 1315$ analysis procedures
- For each procedure, compute $\mathrm{AIC} \equiv \chi^2 + 2k + 2N_{\rm cut}$

  # of removed data points ($N_{\rm cut}$)

  # of fit parameters (k)

Procedures for the hyper quark-mass extrapolation

- Try the five fit ansatze

- Systematically include data points with $am_{\mathrm{PS}} < 1$ and $am_{\mathrm{ps}} < 1$

  → 263 data sets

- $263 \times 5 = 1315$ analysis procedures

- For each procedure, compute $\mathrm{AIC} \equiv \chi^2 + 2k + 2N_{\mathrm{cut}}$

  $2N_{\mathrm{cut}}$ → # of removed data points

  $2k$ → # of fit parameters

- Probability weight $W = \dfrac{1}{\mathcal{N}} \exp\left[-\dfrac{1}{2}\mathrm{AIC}\right]$

Fit results for $m_{\Lambda_{\rm CB}}$

- Polynomial terms in baryon chiral perturbation theory

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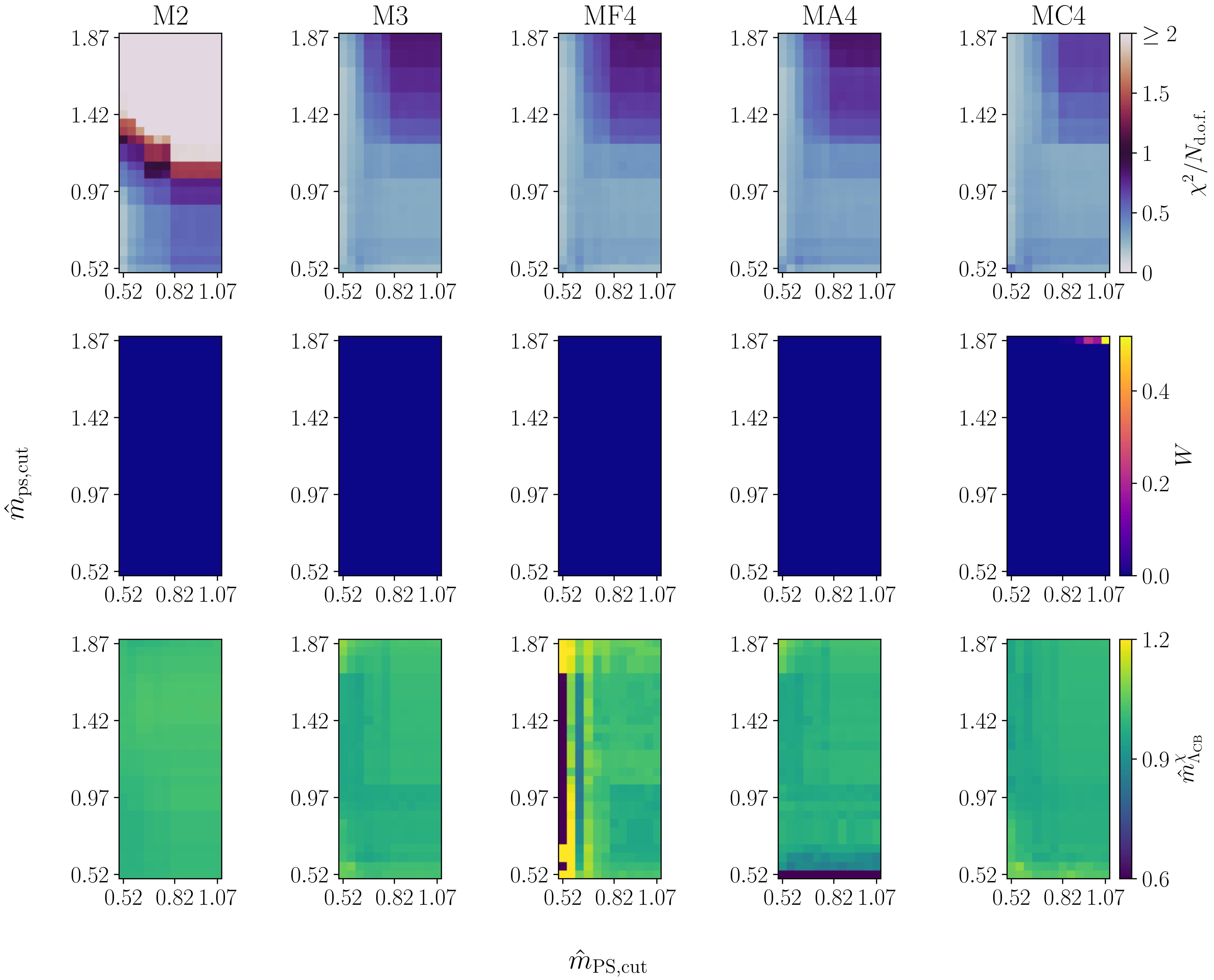
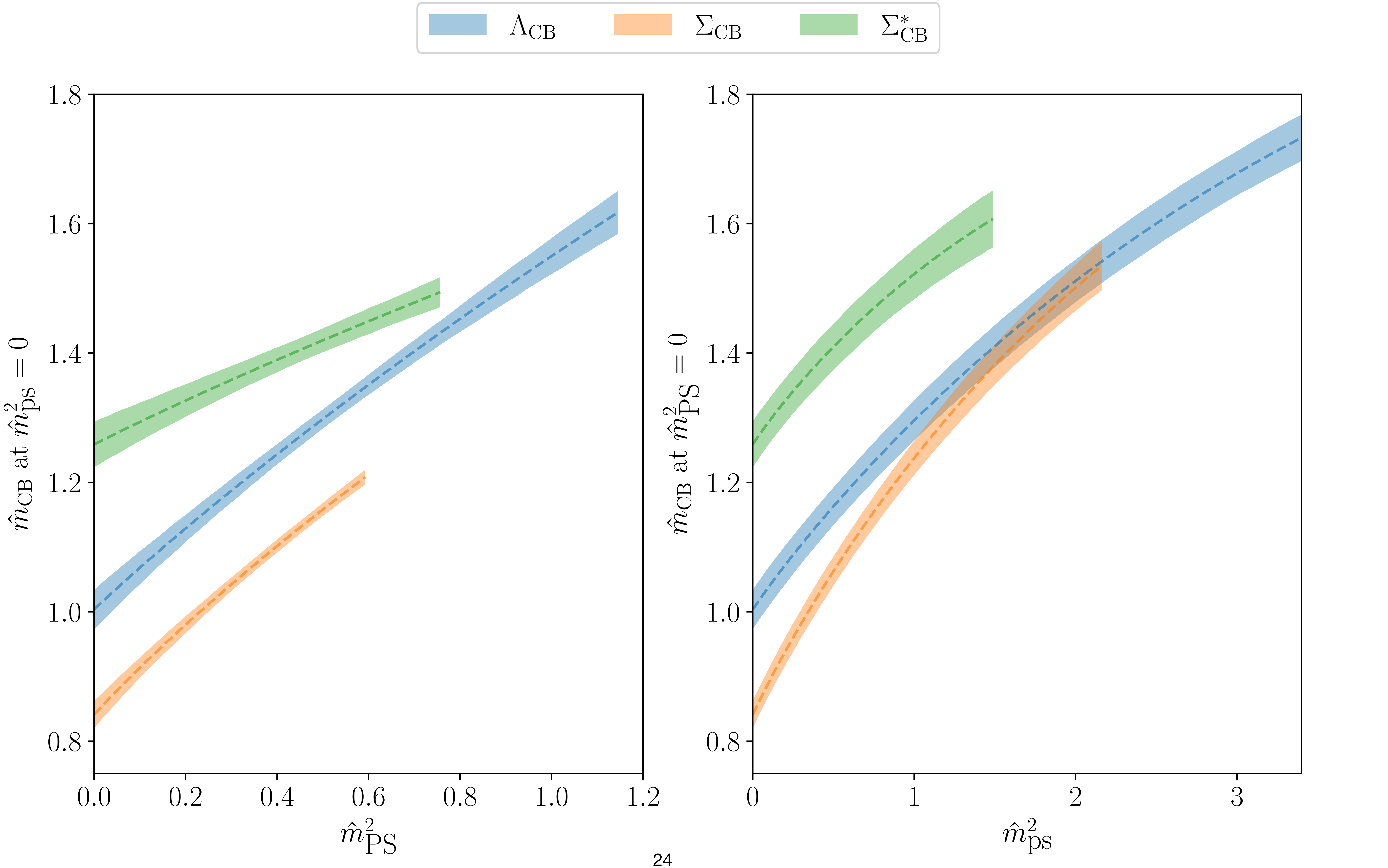
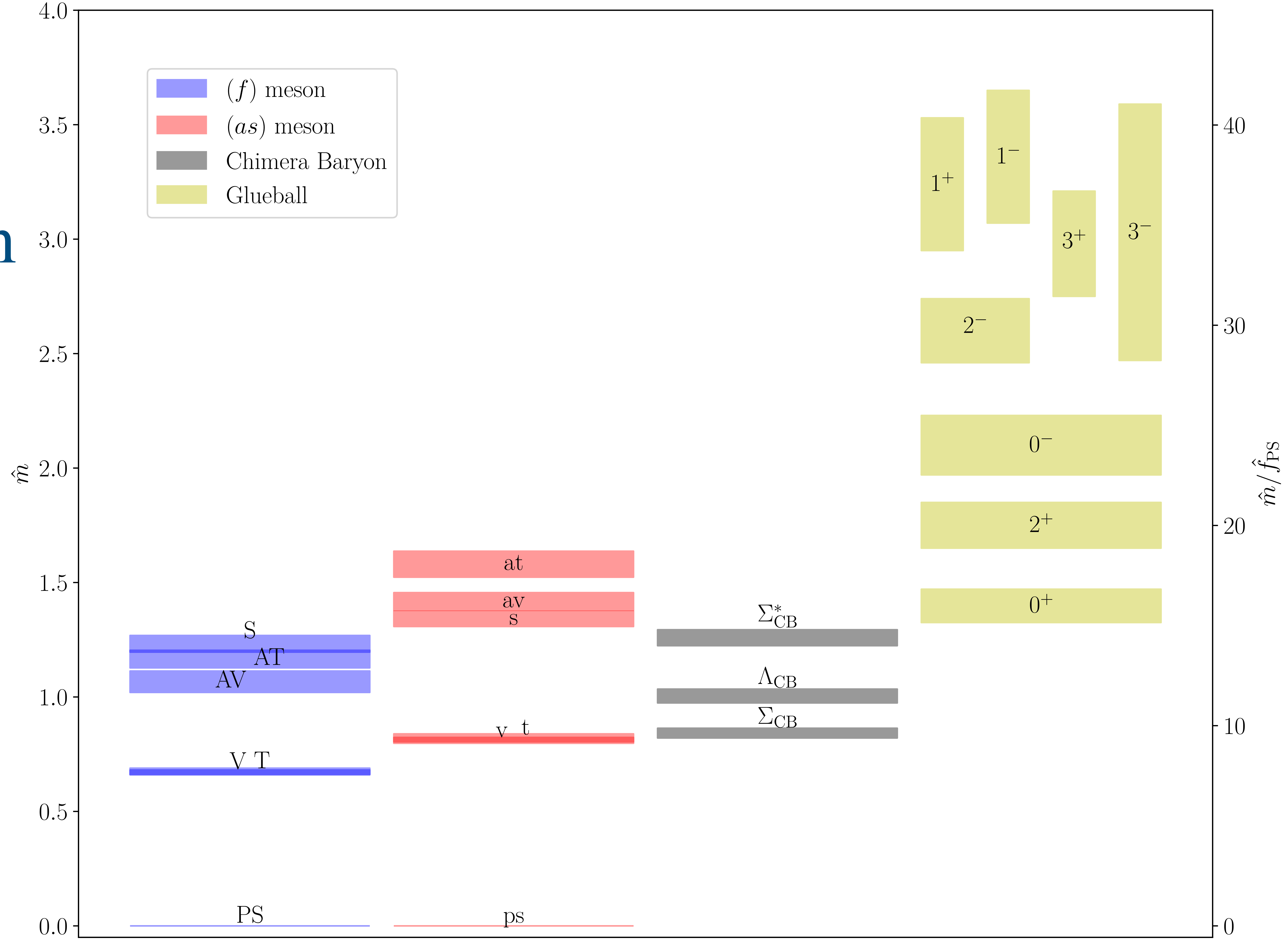


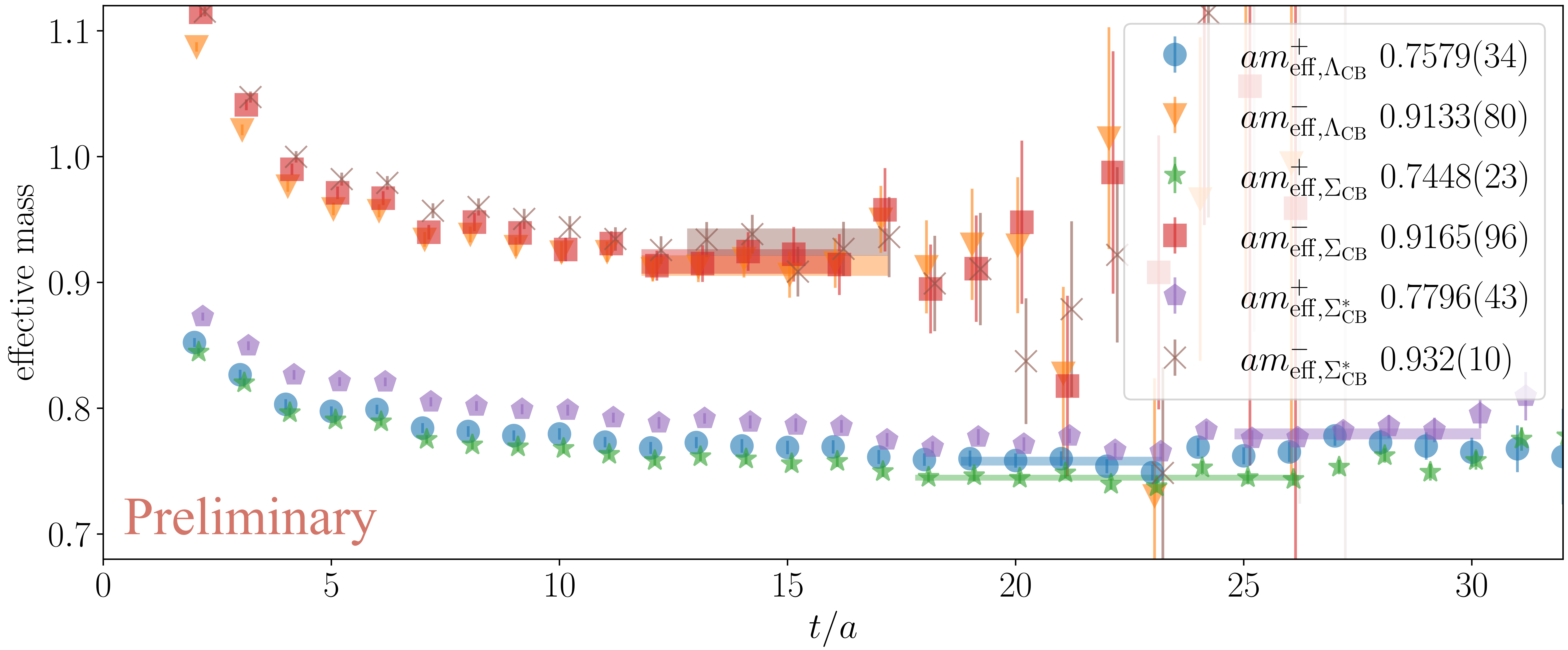
Hyperquark-mass dependence



Quenched spectrum



Preliminary results from dynamical simulation

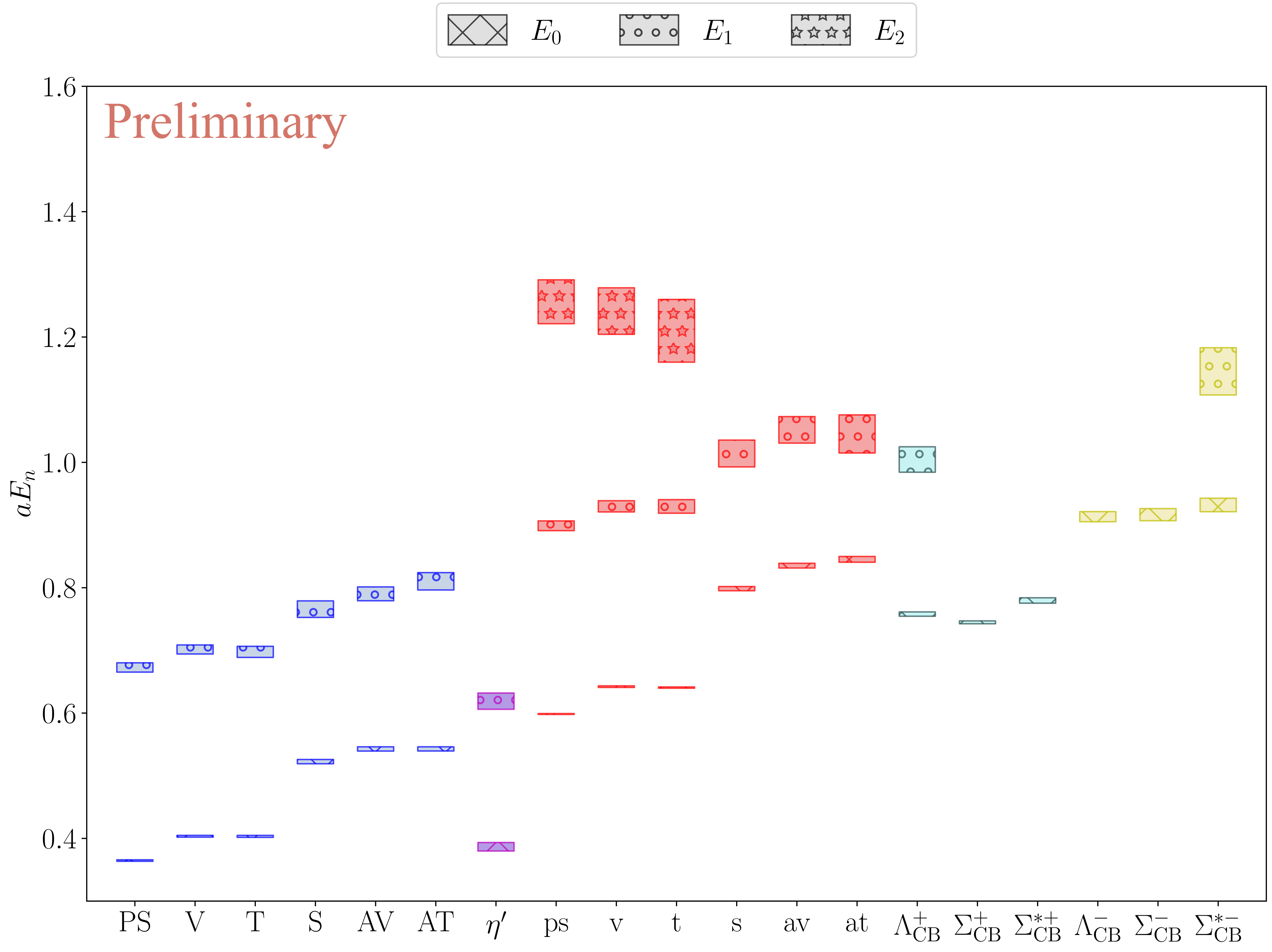


Effective mass plots of chimera baryons measured on fully dynamical ensemble M2. The masses displayed in the legend are extracted by solving the GEVP, using various smearing-level operators as the basis.

Preliminary results from dynamical simulation

Figure: spectrum of ensemble M2.

$(am_0^{(f)}, am_0^{(as)}) = (-0.71, -1.01)$



Conclusion and outlook

- First lattice study of the chimera baryon masses in the Sp(4) gauge theory
  → Key difference from QCD: Λ_{CB} may not be lighter than Σ_{CB}
- Fully-dynamical simulations in progress
- Mixing strength with the top quark, also large anomalous dimension
- Also in the Sp(4) gauge theory: inputs for the Higgs potential

Backup slides

Fit results for $m_{\Sigma_{\rm CB}}$

- Polynomial terms in baryon chiral perturbation theory

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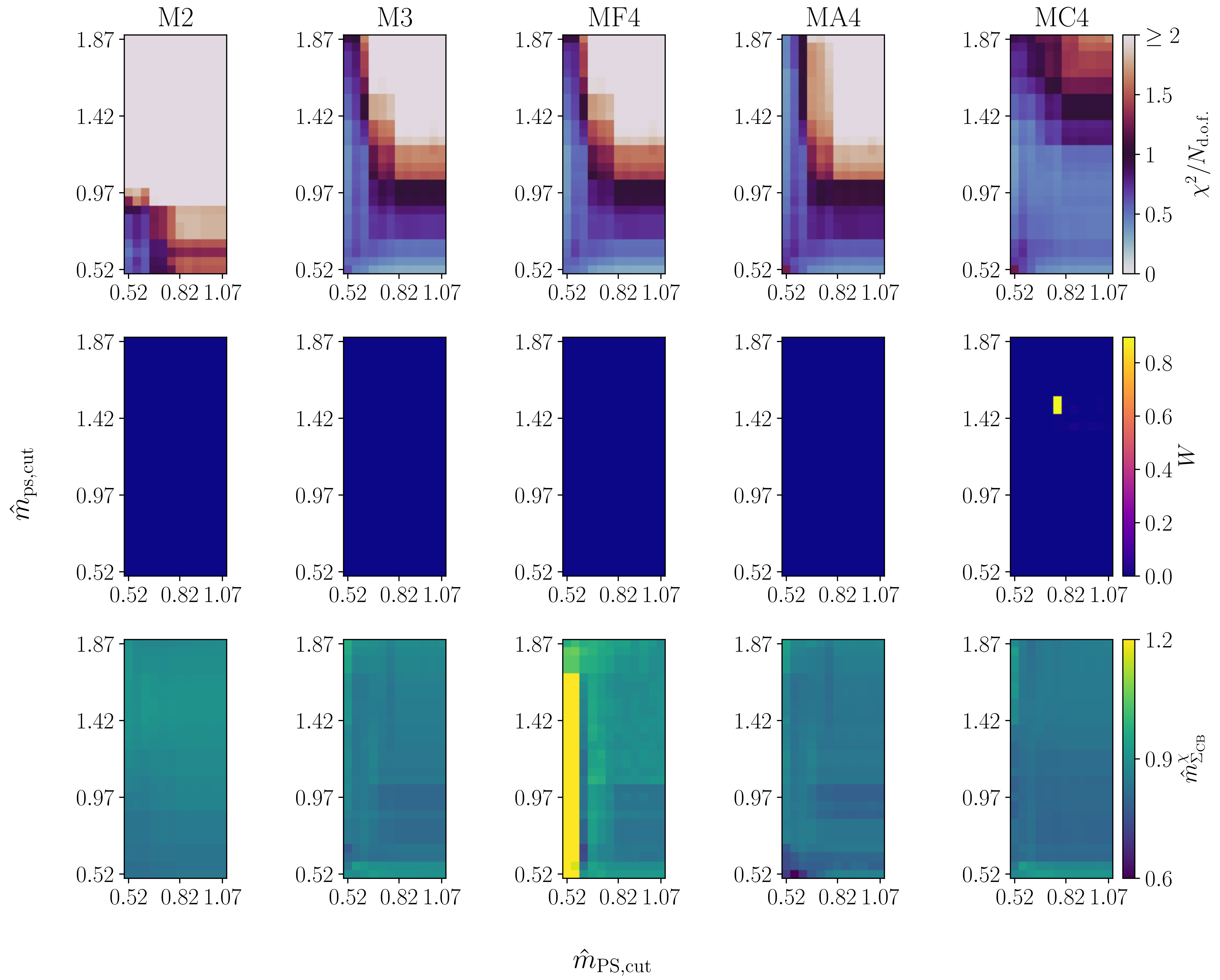

Fit results for $m_{\Sigma^*_{\rm CB}}$

- Polynomial terms in baryon chiral perturbation theory

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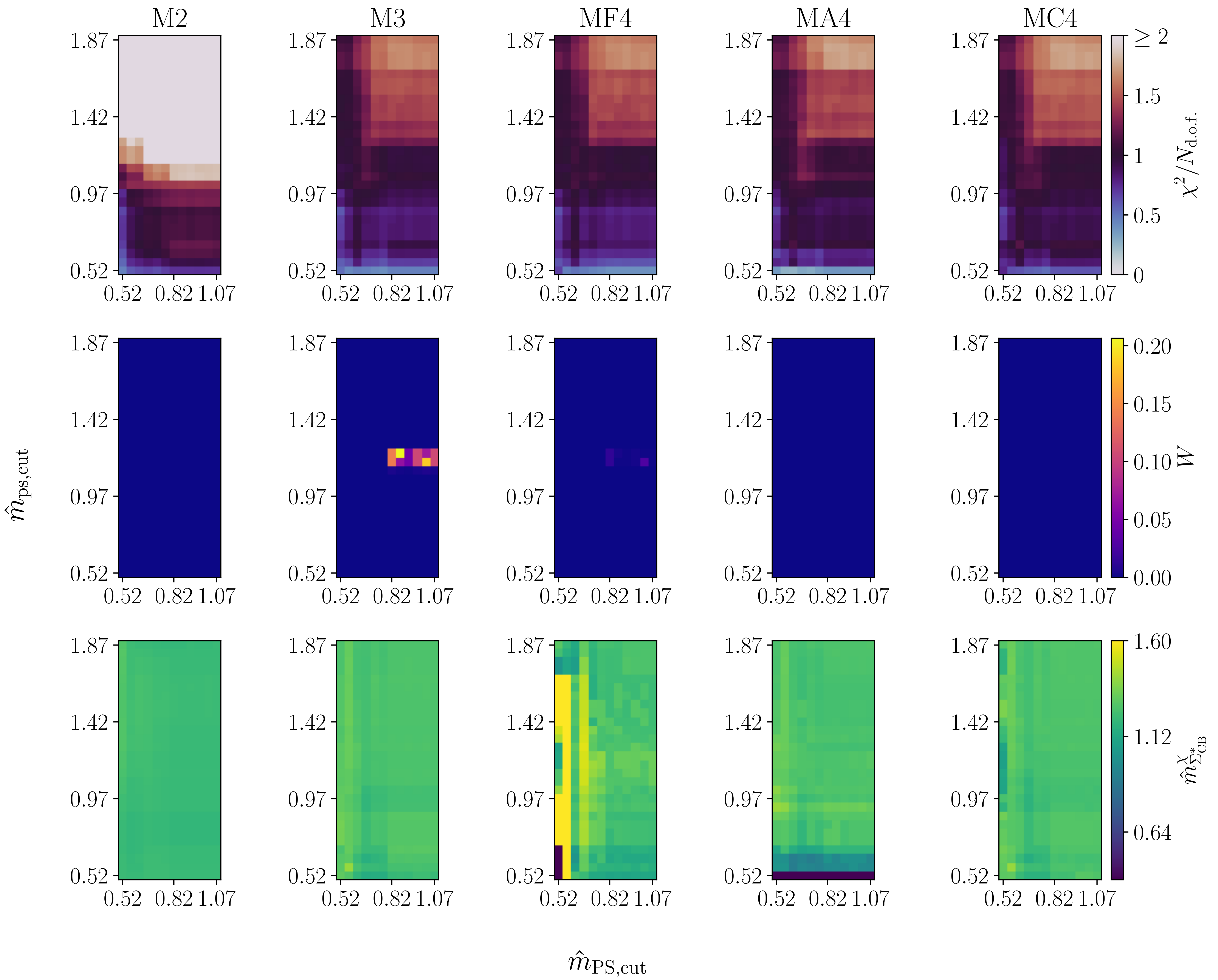
$$\text{M3 ------} \quad + F_3\hat{m}^3_{\rm PS} + A_3\hat{m}^3_{\rm ps} + L_{2F}\hat{a}\hat{m}^2_{\rm PS} + L_{2A}\hat{a}\hat{m}^2_{\rm ps}$$

$$\underbrace{+ F_4\hat{m}^4_{\rm PS}}_{\rm MF4} \underbrace{+ A_4\hat{m}^4_{\rm ps}}_{\rm MA4} \underbrace{+ C_4\hat{m}^2_{\rm PS}\hat{m}^2_{\rm ps}}_{\rm M4C}$$



Gauge group repn and global coset

M. Peskin, 1980

★ Real : $(T^a)^* = (T^a)^{\mathrm{T}} = -S^{-1} T^a S, \qquad SS^* = 1.$

★ Pseudoreal : $(T^a)^* = (T^a)^{\mathrm{T}} = -S^{-1} T^a S, \qquad SS^* = -1.$

$$\Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} \equiv \begin{pmatrix} \psi_\alpha \\ \bar{\chi}^{\dot\beta} \end{pmatrix} = \begin{pmatrix} \psi_\alpha \\ (\chi^\beta)^* \end{pmatrix}, \quad \overline{\Psi}\Psi = \epsilon^{\alpha\beta} \chi^{ia}_\beta \psi_{\alpha i a} + \text{h.c.}$$

gauge repn	condensate	global symmetry
Complex	$\epsilon^{\alpha\beta}\psi^{i(\bar r)}_\beta \psi^{(r)}_{\alpha i} + \text{h.c.}$	$SU(N_f) \times SU(N_f) \to SU(N_f)$
Real	$\epsilon^{\alpha\beta}\psi^{ia}_\beta \psi^{b}_{\alpha i} S^{-1}_{ab}$	$SU(2N_f) \to SO(2N_f)$
Pseudoreal	$\epsilon^{\alpha\beta}\psi^{ia}_\beta \psi^{jb}_{\alpha} S^{-1}_{ab} E_{ij}$	$SU(2N_f) \to Sp(2N_f)$

The top partner and the top mass

$$\Psi_{ij}^{\alpha} = (\psi_i \chi^{\alpha} \psi_j), \; \Psi_{ij}^{c,\alpha} = (\psi_i \chi^{c,\alpha} \psi_j)$$

$$\mathcal{L}^{\rm mix} = -\frac{1}{2}\left\{ \lambda_1 M_* \left(\frac{M_*}{\Lambda}\right)^{d_\Psi - 5/2} \Psi_1^T \tilde{C} t^c + \lambda_2 M_* \left(\frac{M_*}{\Lambda}\right)^{d_{\Psi^c} - 5/2} t^T \tilde{C} \Psi_2^c + \right.$$
$$\left. + \lambda M_* \left[\Psi_1^T \tilde{C} \Psi_1^c \; + \; \Psi_2^T \tilde{C} \Psi_2^c\right] + y v_W \left[\Psi_1^T \tilde{C} \Psi_2^c \; + \; \Psi_2^T \tilde{C} \Psi_1^c\right] \right\} + \text{h.c.}$$

$$m_t^2 \simeq \frac{\lambda_1^2 \lambda_2^2 y^2 \left(\frac{M_*}{\Lambda}\right)^{2d_\Psi + 2d_{\Psi^c} - 10} v_W^2 M_*^4}{m_1^2 m_2^2}$$

where

$$m_1^2 \simeq \left(\lambda^2 + \lambda_1^2 \left(\frac{M_*}{\Lambda}\right)^{2d_\Psi - 5}\right) M_*^2 \, ,$$

$$m_2^2 \simeq \left(\lambda^2 + \lambda_2^2 \left(\frac{M_*}{\Lambda}\right)^{2d_{\Psi^c} - 5}\right) M_*^2$$

- ★ Need $d_\Psi = d_{\Psi^c} < 5/2$, *ie*, large anomalous dimension
  - ➔ IR conformality with more fermion flavours?
- ★ These couplings can be important for Higgs potential
  - ➔ Four-fermion operators

Composite Higgs with Sp(4) gauge group

J. Barnard, T. Gherghetta, T.S. Ray, 2014

Field	$Sp(4)$ gauge	$SU(4)$ global
A_μ	10	1
ψ	4	4

- ★ Two Dirac fermions in the fundamental repn
  pseudoreal
- ★ The Higgs doublet in the coset $SU(4)/Sp(4)$
- ★ The SM $SU(2)_L \times SU(2)_R$ in the unbroken global $Sp(4)$